The Journal of

THE ROYAL AERONAUTICAL SOCIETY

AUGUST 1947 · NO 440 · VOL. 51

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THE ROYAL AERONAUTICAL SOCIETY
4 HAMILTON PLACE, PICCADILLY, LONDON, W.1

AUGUST NOTICES 1947

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members (or non-members) will contribute papers on their own special subjects.

CONTENTS OF THE AUGUST JOURNAL

The Development of the Goblin Engine, by E. S. Moult., B.Sc., M.I.Mech.E., A.F.R.Ae.S.

Useful Load Ratio with Jet and Airscrew Propulsion of Aircraft, by Bo K. O. Lundberg, A.F.R.Ae.S.

Stability of an Aircraft Structure in a Strength Test Frame, by P. B. Walker, M.A., Ph.D., F.R.Ae.S.

ANGLO-AMERICAN AERONAUTICAL CONFERENCE

Members are reminded that application forms for membership of the Anglo-American Aeronautical Conference, 3rd-6th September, were enclosed with the JUNE Journal and Monthly Notices. Eighteen papers will be read and discussed during the Conference. These papers will not be published in the *Journal*, but will be published separately.

GARDEN PARTY AND GUILDHALL DINNER

Members are reminded that application forms for tickets for the Garden Party (Radlett, 14th September, 1947) and for the Dinner at Guildhall (9th September, 1947) were enclosed with the JULY Journal and Monthly Notices. Early application is advised for both functions as the numbers to either will be strictly limited and cannot be exceeded in any circumstances.

ELLIOTT MEMORIAL PRIZE

The Elliott Memorial Prize has been awarded to Corporal Air Apprentice A. E. Dyer for the highest marks obtained by the August 1944 Entry in the General Studies Examination.

CLOSING OF THE LIBRARY DURING AUGUST

The Library will be closed for stocktaking from 11th to 23rd August inclusive. Members are requested to return all books which they have on loan from the Library not later than Saturday, 9th August.

MEETINGS HELD IN THE OFFICES OF THE SOCIETY

Meetings have been held during the month in the offices of the Society by the Aeronautical Research Council, Aerodrome Owners' Association, Society of British Aircraft Constructors, Meteorological Research Committee, R.A.E. J.A.C. Materials Committee, Air League of the British Empire, Graduates' and Students' Section.

GLOUCESTER AND CHELTENHAM BRANCH

A visit has been arranged to the Bristol Aeroplane Co. Ltd. to inspect the Brabazon I on Saturday, 23rd August, at 2.30 p.m. The party is limited to 100. Applications should be made to the Hon. Secretary, J. F. Cuss, A.M.I.Mech.E., A.F.R.Ae.S., c/o Gloster Aircraft Co. Ltd., Witcombe, Glos., or to a Committee member.

READING BRANCH—GARDEN PARTY

The Reading Branch Garden Party will be held on Saturday, 6th September, 1947, from 2.30 p.m. until about 6 p.m. There will be a Grand Fly Past at about 5 p.m.

A limited number of tickets will be available at 5/- per head to all members of the Society and to the Branches of the Society. The tickets will include tea and car park and/or Aircraft park. There will be no landing fees for aircraft which arrive before 2 o'clock. Service will be available for such aircraft.

Applications for tickets should be made, with remittance, to the Secretary, Reading Branch:—B. Buck, Esq., A.F.R.Ae.S., Miles Aircraft Ltd., The Aerodrome, Reading, Berks.

GRADUATES' AND STUDENTS' SECTION

Discussion

A discussion on the "Structural Design of Wings" will be held at 7.30 p.m. on Tuesday, 23rd September at the Society, 4 Hamilton Place, W.1. The Discussion will be introduced by Mr. F. Tyson, A.F.R.Ae.S., Assistant Chief Stressman, Handley Page Ltd.

Visits

30th August, 1947 (*Saturday*)—A visit has been arranged to the works of Miles Aircraft Ltd., Reading, at 2.30 p.m.

17th September, 1947 (*Wednesday*)—A visit has been arranged to the works of the de Havilland Aircraft Co. Ltd. at 2.30 p.m.

Dance

The committee have pleasure in announcing that the Section's Annual Dance, open to members and their friends, will be held on Friday, 17th October at the Royal Hotel, Woburn Place, W.C.1. Further details will be published in the September issue of the Journal.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the Journal for the following month.

ASSOCIATE FELLOWSHIP EXAMINATION RESULTS

The following were the successful candidates in the Associate Fellowship Examination held in May, 1947:—

J. M. Allwright, Design (Aero-Engines); G. E. Archdale, Strength of Aeronautical Materials and Structures (First Place), Design (Aircraft); P. W. Baker, Applied Mathematics, Theory of Internal Combustion Engines, Design (Aero-Engines) (First Place); D. F. Barnes, Applied Mathematics, Strength of Aeronautical Materials and Structures; P. B. Benham, Applied Mathematics; A. Berrington, Pure Mathematics; G. B. Bhide, Aerodynamics; G. Boyce, Theory of Machines; P. A. Budden, Aerodynamics; J. J. Bukovsky, Air Transport; H. Busen-Schmidt, Theory of Internal Combustion Engines (First Place); S. A. Caplan, Pure Mathematics; H. K. Cartwright, Pure Mathematics; L. J. Chantler, Pure Mathematics, Theory of Machines; W. G. Clennett, Pure Mathematics (First Place), Strength of Aeronautical Materials and Structures; Aircraft Materials; J. R. Combley, Aerodynamics, Design (Aircraft); H. Cook, Design (Aero-Engines); T. N. Corkhill, Applied Mathematics, Strength of Aeronautical Materials and Structures, Aerodynamics; E. Coton, Applied Mathematics, Aerodynamics, Meteorology; B. G. Cour-Palais, Theory of Internal Combustion Engines; E. N. Crabbe, Aerodynamics; K. D. Crisp, Pure Mathematics, Theory of Machines (First Place); N. S. Currey, Strength of Aeronautical Materials and Structures; Miss J. L. Davis, Pure Mathematics, Strength of Aeronautical Materials and Structures; E. D. Dixon, Pure Mathematics; J. Dolezal, Aerodynamics (First Place), Air Transport (First Place); J. Dorsey, Aircraft Materials; A. A. Down, Applied Mathematics; F. A. Drayton, Aircraft Materials; Miss J. R. Duncan, Pure Mathematics; G. D. Evans, Theory of Machines; A. Fairbrother, Aerodynamics; P. L. E. Gallimore, Aerodynamics; F. R. Gibb, Applied Mathematics, Strength of Aeronautical Materials and Structures, Aerodynamics; Miss D. Gwynne, Pure Mathematics; N. T. W. Harper, Theory of Internal Combustion Engines; L. H. W. Harris, Applied Mathematics; P. A. Hatswell, Theory of Internal Combustion Engines; J. M. Johnston, Applied Mathematics, Strength of Aeronautical Materials and Structures, Design (Aircraft); J. G. Jones, Applied Mathematics (First Place); J. B. E. Keeble, Pure Mathematics; E. D. King, Theory of Machines; R. E. Lambert, Theory of Machines; R. A. Langley, Pure Mathematics, Aerodynamics, Theory of Internal Combustion Engines; M. P. Le Lohe, Applied Mathematics; A. Lewandowski, Design (Aero-Engines); K. Macewicz, Design (Aero-Engines), Theory of Machines; S. H. Masters, Aircraft Materials; R. L. McCallum, Design (Aero-Engines); M. P. McHeffey, Applied Mathematics, Strength of Aeronautical Materials and Structures, Design (Aircraft); G. McIntosh, Strength of Aeronautical Materials and Structures, Aerodynamics; A. Measures, Strength of Aeronautical Materials and Structures; J. A. S. Moir, Pure Mathematics; E. Mucha, Theory of Internal Combustion Engines, Design (Aero-Engines); U. N. Nayak, Theory of Internal Combustion Engines; G. F. Perry, Strength of Aeronautical Materials and Structures; J. W. Piggott, Meteorology and its Application to Aeronautics; K. G. Rendle, Strength of Aeronautical Materials and Structures; G. C. Ricketts, Aerodynamics; J. H. Risdon, Theory of Machines; G. I. Robinson, Applied Mathematics, Strength of Aeronautical Materials and Structures, Design (Aircraft); R. R. Robinson, Pure Mathematics, Strength of Aeronautical Materials and Structures, Aircraft Materials; R. C. Rogers, Theory of Internal Combustion Engines, Aircraft Materials, Applied Mathematics; J. G. Romeril, Theory of Internal Combustion Engines, Design (Aero-Engines); D. N. Scard, Applied Mathematics, Aerodynamics; L. J. A. Sice, Applied Mathematics; L. Stern, Theory of Internal Combustion Engines, Theory of Machines; C. G. A. Stillaman, Aircraft Materials;

R. Szymanski, Applied Mathematics, Design (Aero-Engines); D. L. Taylor, Pure Mathematics; J. B. Thompson, Pure Mathematics; Titmuss, H., Strength of Aeronautical Materials and Structures; J. A. Tupman, Applied Mathematics, Design (Aircraft); R. A. Vair, Pure Mathematics, Strength of Aeronautical Materials and Structures, Aircraft Materials; J. H. Walmsley, Design (Aircraft); J. Walmsley, Pure Mathematics.

ELECTION OF MEMBERS

Fellows

Henry Paterson Fraser (from Associate Fellow), Stanley George Hooker (from Associate Fellow).

Associate Fellows

Rowland William Angell, Leslie George Bednell, William Norman Blacklock, Frederick Wiliam Robert Bird (from Associate), Francis Charles Bradley (from Associate), Geoffrey Frank Briginshaw (from Graduate), Richard Henry Corthorn Brousson (from Graduate), Cyril Douglas Brown, Cecil John Carter, Horace William Clarke, Athol Henry Fear, Albert Henry Figg (from Graduate), Arthur Ernest Fishlock (from Associate), Frank Leslie Garton, Maurice Alfred Glasspole (from Associate), Leonard Edgar Good, Douglas Gerald Seafield Grant (from Associate), Frederick Rowland Grey, Frederick John Hamilton, Saleh Helmy, Victor Alexander Higgs, Martin Owen Hook, Eric Stanley How (from Graduate), Stanley Peerman Hutton, Thomas Albert Knight, Alfred Stanley Knowles, Mark Dawson Knowles, Peter Stevens MacGregor, Bernard Walter Martin (from Graduate), Harry Maynard (from Graduate), Mahadeo Vinayak Namjoshi, Christopher Bernard Vere Neilson, Sidney Joseph Paine (from Associate), John Joseph Parkes, Cyril Henry Penn, Courtland Davis Perkins, Frederick Noel Pierce, Gordon Powell, Arthur Alfred Puttick, Norman Ring (from Student), Philip Lawton Sumner, Ronald Tatham, Roy Albert Tier (from Student), Frank Lionel Tollow, Cyril Frederick Turner (from Associate), Raymond Hedley Vernon (from Graduate), Reginald Thomas Weatherstone (from Graduate), Francis James Prince Whiting.

Associates

Frederick George Banting, Robert William Warren Buckley, Cyril George Butler, Frank Dixon, Denis Edward Hastwell, Alec Henry Jones, John Gordon Lacey, James Bertram Linton, George Alfred Bertram Lord, Patrick J. McEnery, Ralph Wardle Moore, Michael Pierre Perrelet, Theodore Grimmer Raynham (from Student), Frederick Victor Rehill (from Student), William Robb, Gerard Claughton Roberts, Eric William Saben (from Student), Albert Ernest Trevelyan, Denis Frederick Woor, Geoffrey David Puget Worthington.

Graduates

Derek George Ashwell, William Andrew Baker, Harold Charles Beasley, Alan Edmund Clarke, Douglas Ronald James Colpus (from Student), James Arnot Hamilton, Alfred Dennis Jackson (from Student), Aubrey Frederick Walter Langford, John Rutter Lloyd, Lawrence Halford Warren, Ellis Luckraft (from Student), Donald Pratt, John Anthony Staunton, Peter John Vinson (from Student).

Students

Charles Crawford Aitkenhead, Denzil Arthur Ashover, Arthur Francis Becker, Frank Blamire, John Lawrence Budd, Roland Frederick Burgers, Anthony Lambert Cole, Eric Lewis Eavis, William M. Giffen, Derek Michael Gladstone, Harold Frederick Hawkins,

Reginald Arthur Hinkley, William Donald Horsfield, Denis Lawrence Lofts, David Muir Mackie, James Parker, David Windsor Parry, Julien Podolski, Peter Robinson, Christopher John Rogers, Ronald Leon Samuels, Kenneth Robin Warren.

Companion

John Michael Storer Keen.

ACKNOWLEDGMENT

The Council acknowledge with grateful thanks the gift of Aeronautica by Monck Mason and a collection of lantern slides from G. W. Simmons, Esq.

ADDITIONS TO THE LIBRARY

Pamphlets in italics with location reference following in brackets. Books marked * or ** may not be taken out on loan.

A.a.333—Theory of Flight. Richard von Mises. McGraw Hill. 1945.

B.b.73—*Principles of the Helicopter. Dr. Alexander Klemin. Reprint from Aero Digest. Y.3.ivi.*

BB.c.105—Aircraft Propeller Design. F. T. Meacock. Spon. 1947.

E.d.31—British Standards for Workshop Practice. B. S. Handbook No. 2. British Standards Institute. 1946.

G.f.33—*The story of electric welding. Published by "Sheet Metal Industries" for British Electric & Allied Manufacturers' Association.* 1947.

G.e.E.65—Symposium on the Hardenability of Steel. The Iron & Steel Institute. 1946.

G.e.E.66—Crucible Cast Steel. John Vessey & Sons. Sheffield. 1947.

H.b.92.—*The adequacy of the passenger liability limits of the Warsaw convention of* 1929. *J. Brooks, B. Parker. Reprint from Journal of Air Law & Commerce. Vol.* 14. *No.* 1. 1947. (*P.H.*1.).

L.d.116—*Notices to Airmen. Nos.* 156, 157, 158, 159, 160, 161, 162, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 189.

*Q.a.173—Catalogue Générale du Centre de Documentation Aéronautique Internationale. Aero Club de France. 1944.

*Q.a.174—Library Catalogue. 1946. The Bristol Aeroplane Co. 1947.

UC.5/33—*C.S.I.R. Division of Aeronautics. Report S.M.82. The strength of machine parts under fluctuating loads.* 1946. *M. S. Paterson and H. A. Wills. Aeronautical Laboratory, Melbourne.*

UC.5/34—*C.S.I.R. Division of Aeronautics. Report S.M.86. On a method of increasing the rate of convergence of some iteration processes. J.P.O. Silberstein. Aeronautical Laboratory Melbourne.* 1947.

*WB.17/18—Nickel Bulletin. Vol. 18, 1945 Mond Nickel Co. London.

A.R.C. Reports and Memoranda—

2104—*A mathematical method of cascade design. M. J. Lighthill.*

2097—*A note on the interpretation of V.g. records. P. E. Montagnon, A. Robinson and S. V. Fagg.*

2126—*The "china clay" method of indicating transition. E. J. Richard and F. H Burstall.*

2131—*N. P. L. Mach number gauge. D. Giles.*

2044—*Velocities and speeds through a shock wave. A. Thom and P. R. Owen.*

2114—*The representation of aerodynamic derivatives. G. Temple.*

2075—*A theoretical analysis of longitudinal dynamic stability in gliding flight. H. M. Lyon, P. M. Truscott, E. I. Auterson and J. Whatham.*

2101—*Examples of the application of Busemann's formula to evaluate the aerodynamic force coefficients on supersonic aerofoils. C. N. H. Lock.*

The following reports have also been received:—

Publications Scientifiques et Techniques du Ministère de l'Air.

Bulletins des Services Techniques. No. 109.

Notes Techniques. No. 24.

J. LAURENCE PRITCHARD,
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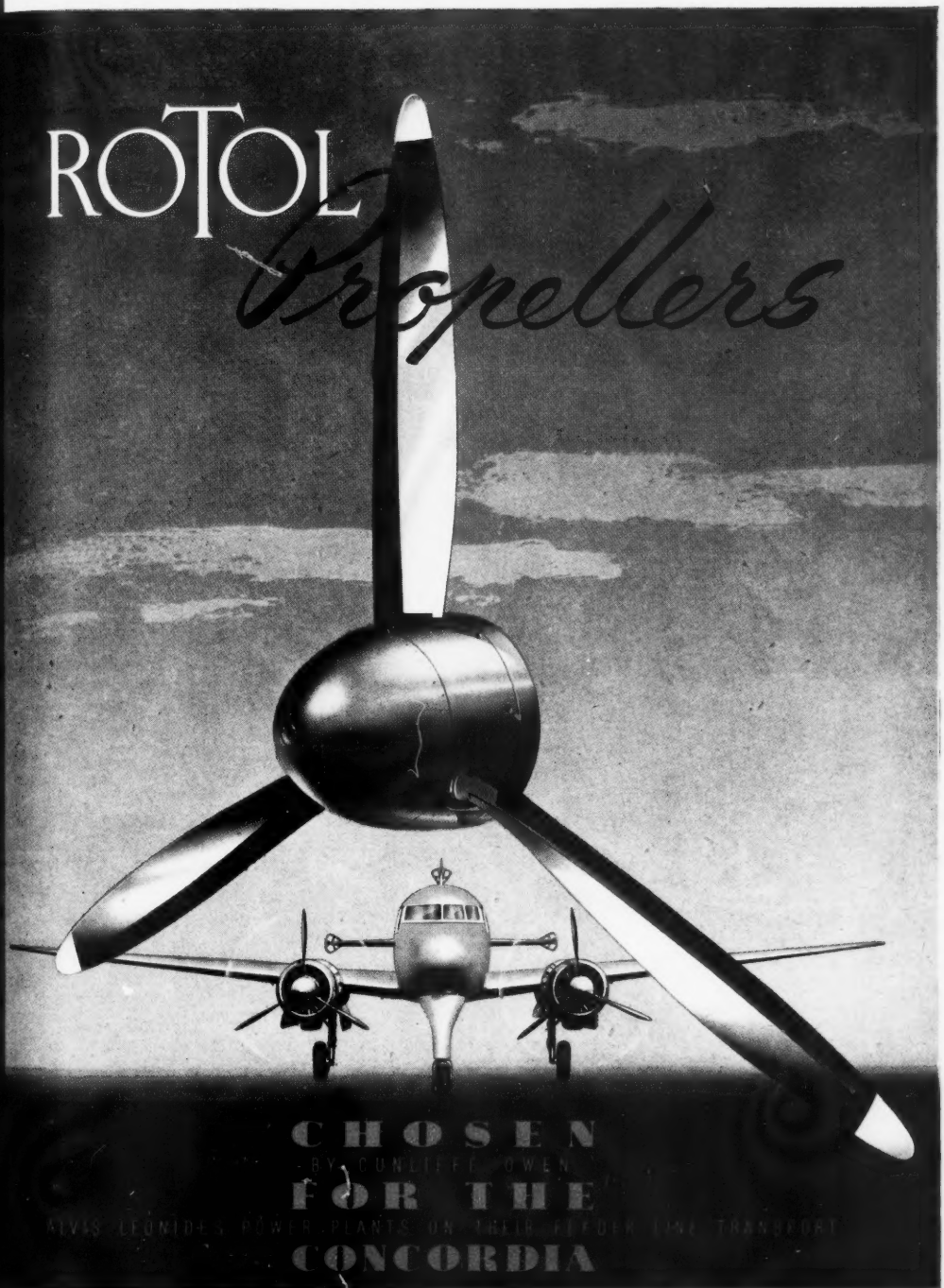

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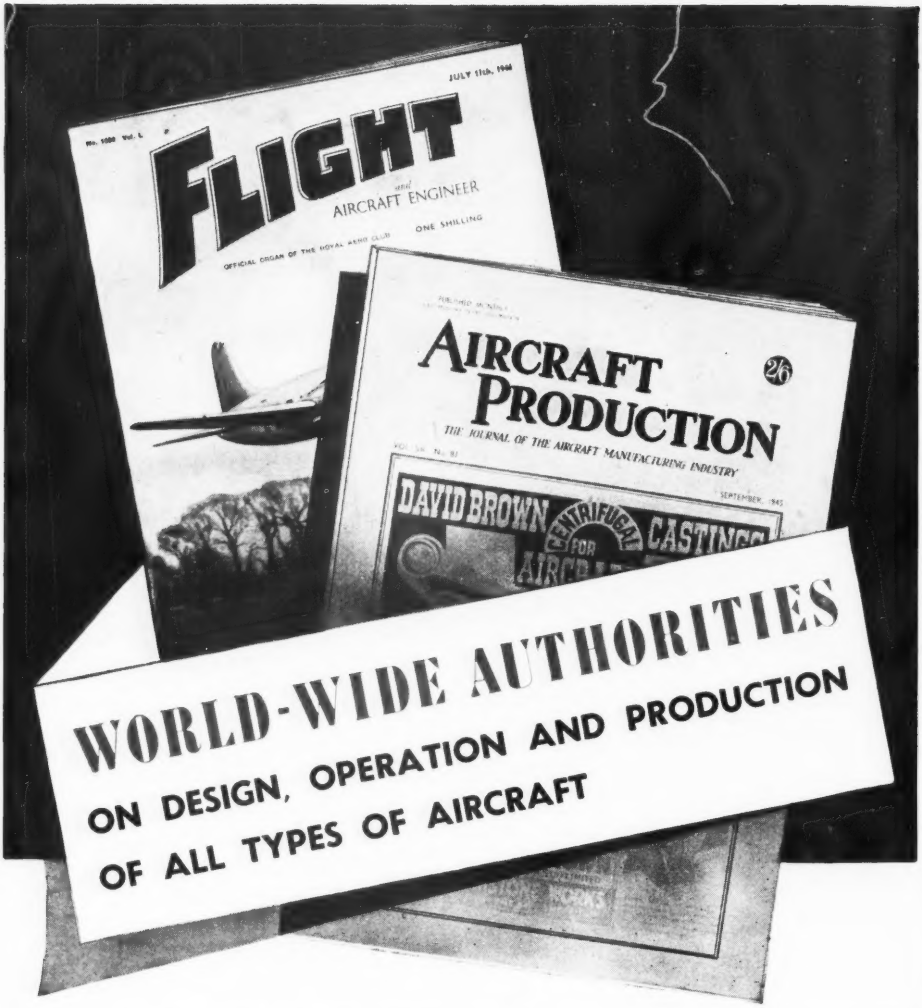

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Published in conjunction with these journals, FLIGHT HANDBOOK (212 pages, 7/6 net) is essentially a manual for the student, whilst GAS TURBINES AND JET PROPULSION (272 pages, 12/6 net) by G. Geoffrey Smith, has been widely adopted as the standard text on the subject by Universities, Technical Institutions and Training Centres everywhere.

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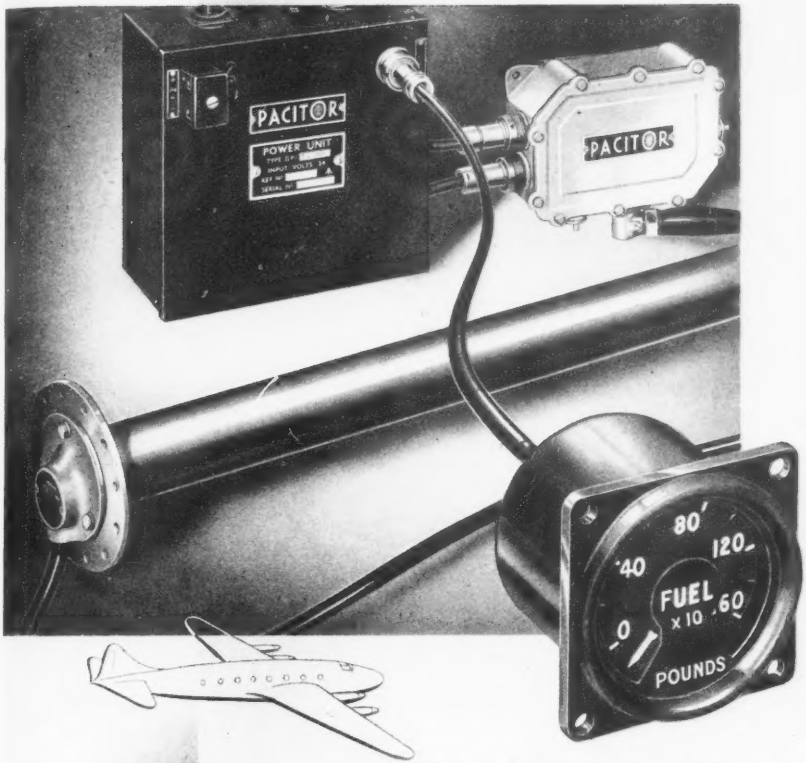

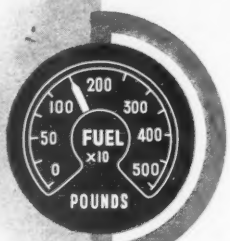

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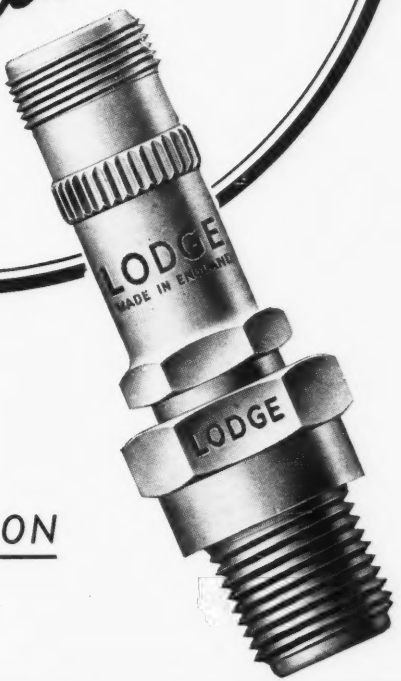

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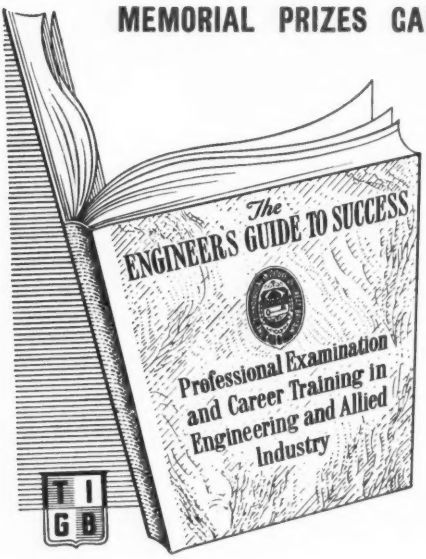

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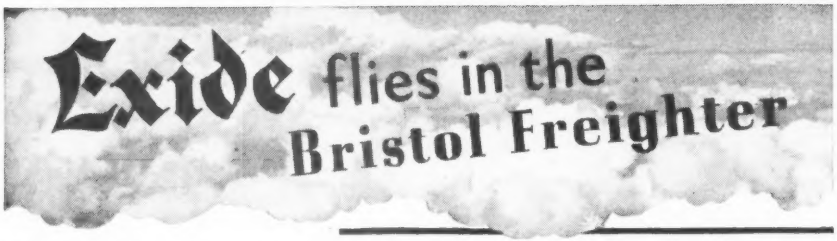

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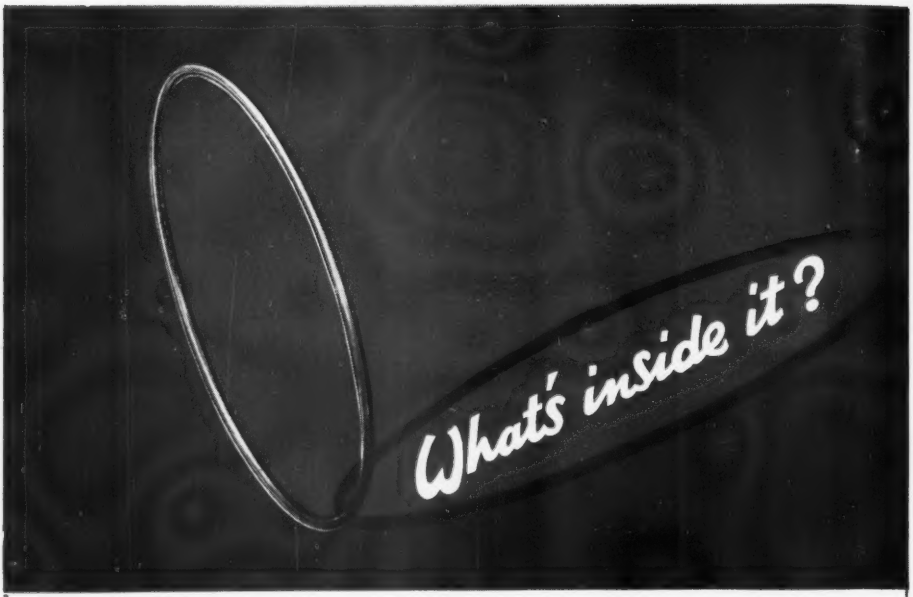

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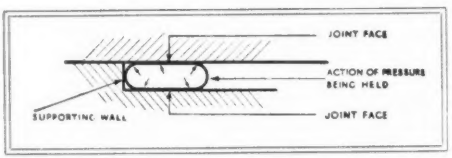

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THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY

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CONTENTS *AUGUST 1947*

THE DEVELOPMENT OF THE GOBLIN ENGINE

By E. S. Moult, B.Sc., M.I.Mech.E., A.F.R.Ae.S. 655—685

USEFUL LOAD RATIO WITH JET AND AIR-SCREW PROPULSION OF AIRCRAFT

By Bo. K. O. Lundbergh, A.F.R.Ae.S. :: 686—703

STABILITY OF AN AIRCRAFT STRUCTURE IN A STRENGTH TEST FRAME

By P. B. Walker, M.A., Ph.D., F.R.Ae.S. :: 704—714

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FLIGHT TO AUSTRALIA IN A SMALL PLANE PROVED SIMPLE AND PRACTICAL

Flying solo in a Miles Gemini, powered with two CIRRUS (Minor) engines, and wearing normal business clothes, Group Capt. Bandidt recently covered 1,000 miles a day on a 13,000 miles flight from this country to Queensland and successfully demonstrated that light aircraft for business travel abroad can be a simple everyday undertaking. On arrival the following telegram was despatched:—

"GROUP CAPTAIN BANDIDT ARRIVED MASCOT 1430 HOURS
FOURTEENTH INSTANT IN MILES GEMINI STOP REPORTS
CIRRUS MINORS NEVER MISSED A BEAT STOP
VERY ELATED WITH RELIABILITY CIRRUS ENGINES."

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The 716th Lecture read before the Society, on 8th May, 1947, at the Institution of Civil Engineers, Great George Street, London, S.W.1. In the chair the Vice-President, Dr. H. Roxbee Cox, F.R.Ae.S.

THE DEVELOPMENT OF THE GOBLIN ENGINE

by

E. S. MOULT, B.Sc., M.I.Mech.E., A.F.R.Ae.S.

Mr. Moult joined Major Halford in 1927 *as Technical Assistant in the design and development of the Gypsy, Napier Rapier, Dagger and Sabre engines. In* 1944 *he was appointed Chief Engineer, de Havilland Engine Co. Ltd.*

1. INTRODUCTION.

WORK on the Goblin engine was started in 1941 when, at the invitation of the Ministry of Aircraft Production, the de Havilland Enterprise began to interest itself in jet propulsion. At this time de Havillands were much in ignorance of the work of Air Commodore Whittle, the Royal Aircraft Establishment and the Gloster Company in this field. The first step was to study what had already been done and in this connection the fullest co-operation was offered by all concerned. The author would like to express the appreciation of the organisation with which he is associated for the material help received in those early days by way of advice, data and drawings. As a result, it was possible to start fully abreast of what was being done in this country. The benefits of further experience and mutual assistance from the pioneers in jet propulsion were fostered by a process of frank discussion and exchange of information, finally to be cemented by the formation of the Gas Turbine Collaboration Committee.

The Ministry did not attempt to lay down the size or the form of power plant which they expected, but invited proposals on what the firm thought would be right. As engine builders, consultations were held immediately with the de Havilland Aircraft Division to obtain their views on the size of unit required for a single-seater fighter intended, in the midst of a war, for quantity production. The conclusion was reached that, for simplicity and ease of production, a single engine was all that was required and that existing or projected jet engines were too small even for the lightest operational fighter that could be envisaged.

It was decided that a thrust rating of about 3,000 lb. would be required at sea level to give a performance that was sufficiently ahead of current Spitfire and Typhoon types to justify the introduction of a new fighter at this phase of the war. At the time this decision was taken a thrust of 3,000 lb. was roughly three times the value of what had been actually achieved — even for short periods—and was considerably in excess of the output of any known projected engine.

The minimum size of a pressurised cabin to house the pilot, the fuel and four guns, gave a permissible diameter for the engine of about 50 inches. It was appreciated that intakes to handle 100 tons of air per hour would be a problem and that one paid a penalty in lost thrust and increased drag for every needless foot of exhaust system.

Thus was born the layout of the D.H.100 aircraft, now in production as the Vampire. Twin booms enabled the control surfaces to be lifted clear of jet interference and provided almost ideal engine accessibility. High-

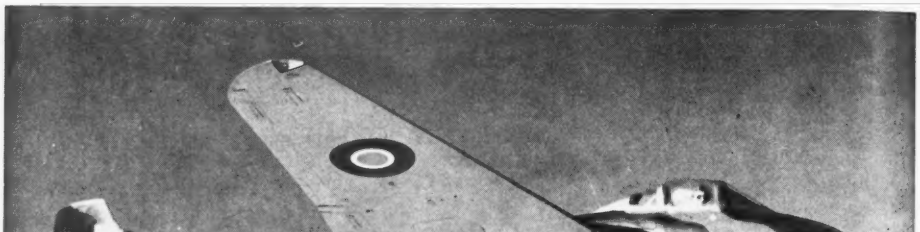

Fig. 1.
Vampire in flight.

velocity ducts in the wing roots reduced the size of the intakes and their interference with the rest of the aircraft and yet provided maximum intake ram. The engine could be overhung from a strong bulkhead aft of the main fuel tank and the tail pipe reduced to a minimum consistent with good lines for the fuselage and the requirements of the exhaust cone assembly behind the turbine. Fig. 1 shows the Vampire in flight and illustrates most of the points described.

From this point, which was reached in April 1941, the layout of the Goblin engine proceeded apace. In all aspects, the design was governed by the war mentality which demanded the fullest exploitation of what was known and the avoidance of those things which, possessing technical attractions, might involve protracted development.

There was the temptation of the axial compressor and its promise of high efficiency. But its characteristics would be sharp, its length greater and it was not possible to take advantage of its smaller diameter. It would involve more man-hours to produce and it would not be so robust.

Whittle had used a double-entry, centrifugal compressor but this involved placing the engine in a pressure box, feeding it with air from large ducts which could not be afforded without spoiling the wing spar and the intake openings. A single-entry compressor could almost touch the skin of the fuselage and would permit the use of an impeller large enough to handle the air flow required. It won the day.

Having decided on a single-entry compressor, the possibility arose of going to an annular combustion chamber with greater simplicity and increased combustion space. Most of the practical work had been done on individual chambers and there was no air supply available of sufficient capacity separately to blow a complete annular chamber and test it under working conditions. These considerations swayed the decision to employ individual chamber assemblies.

2. GENERAL DESCRIPTION OF GOBLIN II ENGINE.

Figure 2 shows an external view of the Goblin II engine as in current production. The photograph shows the bifurcated intakes to the compressor which line up with the ducts in the wing roots, the compressor casing which contains a single-entry impeller and the diffuser casing where the velocity of the air leaving the impeller is largely converted

to pressure and is deflected into the combustion chambers. The sixteen straight-through combustion chambers converge in a junction box assembly before the turbine, whose sole duty is to extract enough power from the gases to drive the compressor. The residual energy is concentrated in the exhaust cone assembly and the reaction of the gases ejected from the propelling nozzle produces the forward thrust. The engine is supported in the case of the Vampire from four bolts at the front of the compressor casing. Alternatively, four pads are provided on the periphery of the compressor casing which can be used for mounting purposes.

More details of the internal construction are revealed in Fig. 3. The main rotor is supported in two ball bearings and the turbine wheel is connected to the compressor by a rigid, large diameter shaft. At full duty, this shaft transmits 6,000 h.p. at take-off and this power rises to over 8,000 h.p. at 650 m.p.h. because of the greater mass flow arising from the effects of ram in the air intakes. The actual stresses in the mainshaft are purely nominal and its generous proportions are dictated by the lateral stiffness necessary to place the whirling speed of the rotor well beyond the maximum speed of rotation.

Air pressure at the back of the impeller diaphragm tends to move the rotor forward and the pressure drop across the turbine blades produces a rearward thrust on the rotor. By careful selection of the diameter of the sealing rings on the back of the

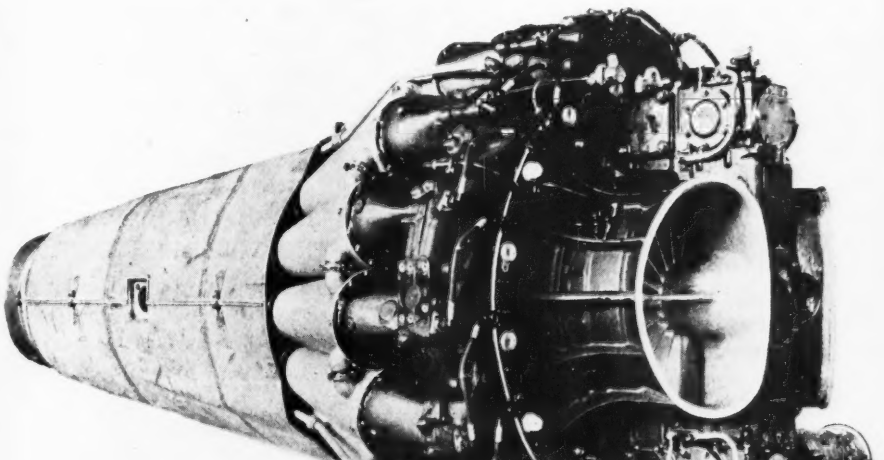

Fig. 2.
External view of Goblin II engine.

impeller, it has been possible to adjust conditions so that these effects neutralise and only a small residual thrust is carried by the locating bearing in front of the impeller. The rear bearing is mounted in a cylindrical housing and is free to slide longitudinally in order to allow for the effects of differential expansion.

Support for the rear bearing and turbine assembly is provided by a conical steel casing which is attached to the compressor at its forward end by strong bolts passing through the diffuser casing. Four of these bolts carry extension lugs for mounting purposes as already mentioned. Thus from the pick-up points to the turbine is an all-steel assembly whose rigidity has enabled complete cantilever suspension to be so successfully employed.

The static blades of the turbine, the turbine shroud and the tail assembly are supported from the rear bearing housing by a crimped diaphragm plate which is torsionally stiff to take the reaction of the stator blades, but radially flexible to allow for the appreciable expansion of the hot nozzle box assembly. Further support to the tail assembly is provided by a light cylindrical supporting ring and by diagonal ties which pass from the main casing to the turbine shroud between the individual spouts of the junction box assembly. These members transmit moments from the tail assembly which arise from "g" loads in flight or when landing.

Cooling of the turbine bearing is an important matter on any gas turbine engine. In the Goblin engine, air is bled from the compressor, cooled in a jacket surrounding the air intake and passed through spaces under the inner race and outside the outer race. After passing the bearing, the cooling air is deflected across the upstream face of the turbine disc before it mingles with the main gas stream at the turbine nozzles. Additional air, not cooled in this case, passes through the hollow struts of the tail assembly and is discharged at the centre of the rear of the turbine disc. Thus, the turbine wheel is air-cooled on both sides and there are no close labyrinths or rubbing seals in the turbine assembly. This system of differential pressure sealing has eliminated at least one difficulty of current turbine design.

The drive to the accessories is from a bevel cluster mounted in front of the impeller. Vertical drive shafts pass between the bifurcated intakes and, through further bevels, drive the top and bottom accessory boxes. The main rotor bearings are fed with a small quantity of oil from two metering pumps which ensure positive lubrication without danger of undue losses or excessive leakages. The oil metered to the rear bearing—about 0.5 pint per hour—is drained overboard and is lost. This quantity constitutes the total oil consumption of the engine.

Ventilation of the engine bay and protection of the airframe from radiation by the hot metal parts of the turbine and tail pipe is obtained from a venturi device surrounding the propelling nozzle. The venturi device induces a gentle flow of cooling air in the space between the tail pipe and a light sheet-metal shroud member.

3. STAGES IN THE DEVELOPMENT OF THE GOBLIN ENGINE.

The first drawings of the Goblin engine were issued to the shops in August 1941 and 248 days later the prototype engine ran on the test-bed—in April 1942. From the beginning much importance was attached to a full and proper representation of the installed intake arrangements. A few days after this first test, the particular intakes used then were the cause of a minor disaster when they collapsed inwards because of the unexpectedly high suction of the impeller. Fortunately, this followed the official acceptance test!

Initial troubles were associated with starting, buckling of the tail pipe and shortage of capacity of the fuel pump. By devious means

GOBLIN 2 JET PROPULSION UNIT

STATIC THRUST 3000 LB.

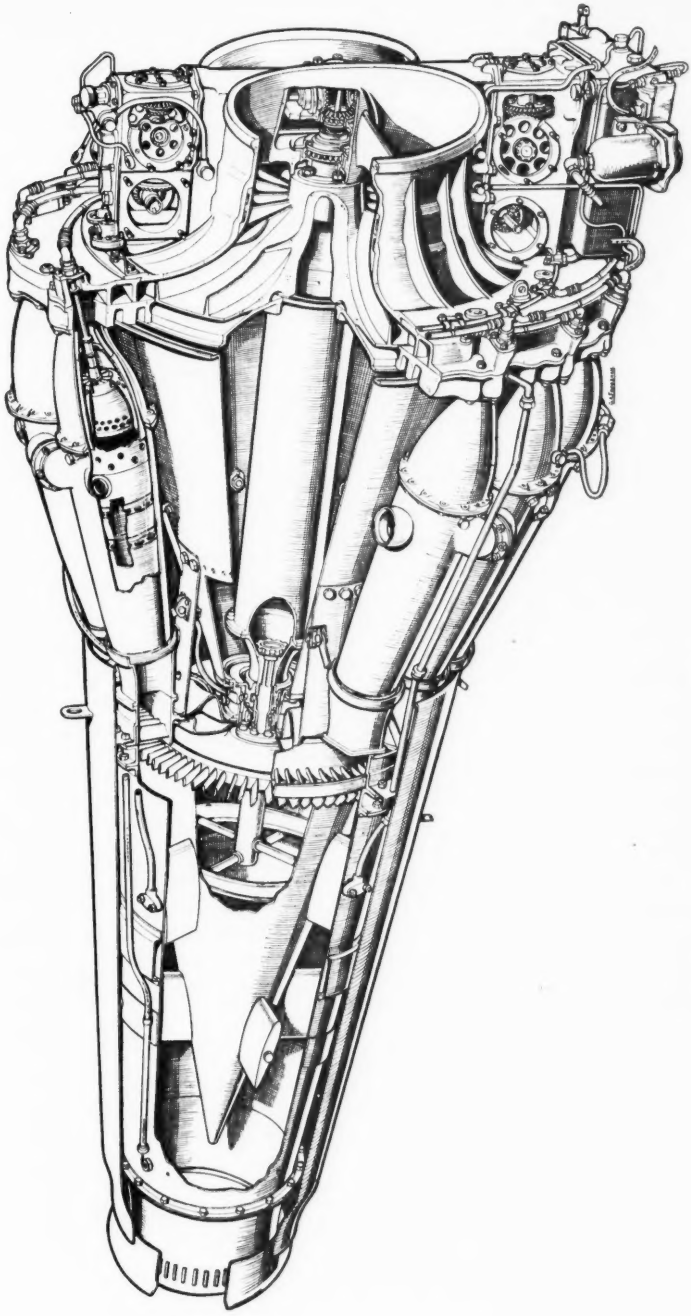

Fig. 3.
Cut-away view of Goblin engine.

these shortcomings were temporarily overcome and the Goblin engine was run up to full speed for the first time on 13th June 1942. Table I compares the figures obtained with the design condition.

TABLE I.

	Design Condition	Observed on Test 13/6/42
Speed—r.p.m.	10,500	10,500
Thrust—lb.	3,000	3,010
Specific fuel cons. lb./lb. thrust/hr.	1.15	1.23
Jet pipe temperature °C	670°	*625°

These results were most encouraging, but it took a further 2½ years of hard work before reliability in the form of type approval at a comparable rating was established.

About this time the firm's commitments on the aircraft side were exceptionally heavy —particularly in relation to the programme of Mosquito production— and it was inevitable that the completion of the first D.H.100 was delayed. For these reasons, an airframe was sought in which flight experience with the Goblin engine might be obtained and a visit was paid to the Gloster Company to consider the adaptability of their new F.9/40 project. At first sight the twin-ducted intakes of the Goblin were prohibitive in a nacelle installation, but Mr. Carter, of the Gloster Company, made the brilliant suggestion of turning the engine through 90° so that the bifurcated intakes passed neatly above and below his wing spar and reunited in a circular intake at the nose of the nacelle. As far as the engine was concerned, this proposal involved some reorganisation of the lubrication system and the disposition of the oil sump, but was otherwise straightforward.

By September 1942, an engine had been built to the Gloster standard and had completed the 25-hour Special Category test necessary for flight approval. Other engines to the same standard were completed, installed in the F.9/40 and the prototype of the Meteor first flew with Goblin engines from Cranwell in the hands of Michael Daunt early in the morning of 3rd March 1943.

For these initial flights the engines were rated at 2,000 lb. thrust. Although a total of 4,000 lb. was considerably more than was necessary for flight, this relatively easy rating enabled the Goblin to obtain a good deal of experience in the air at a duty well within its capacity and hence with a fair degree of reliability.

Initially, the power required to start the engine had been underestimated and so the first engines flew with two starter motors. Much work had to be done on the fuel system before satisfactory starts were obtained automatically, as opposed to the "sleight of hand" methods of the first bench tests. Combustion was unsatisfactory and inspections were necessary at 5-hourly intervals on flame tubes and fuel pumps to ensure safety of operation. At the time of the first flight something like 200 hours of bench testing had been completed.

In the following months invaluable experience was obtained in the air and on the test bed and modifications were introduced which speedily showed improvements in general behaviour and reliability. By the time the first Vampire flew in September 1943, the maximum r.p.m. had been raised from 9,000 to 9,500 r.p.m. and the thrust increased to 2,300 lb. An additional strip of aerodrome had been prepared at Hatfield but take-off, even with 2,300 lb. thrust, was easy and the extension was unnecessary. At the end of 1943 the total running time on the bed was about 700 hours and complete data had been obtained to altitudes of 35,000 ft. and at speeds approaching 500 m.p.h.

This progress excited a good deal of interest in America and a jet-propelled fighter

*This temperature is lower than estimate since the thermocouple only recorded about 50 per cent. of the dynamic effect.

incorporating the Goblin engine was designed and built in record time by the Lockheed Corporation. The aircraft was known as the XP.80 and subsequently became the "Shooting Star."

The pressure of bench and flight development was exceedingly heavy at that stage and it was with the greatest difficulty that development engines were made available to meet the new demand. A special dispensation of the war-time restriction was obtained to enable a lorry with lights ablaze to proceed to Scotland, whence the Goblin—complete with a de Havilland engineer—was flown direct to California. It was with dismay that the news was received of severe damage to the first engine by a collapse of the intake ducts during the initial ground tests. In less than a month, the test engineer had returned from California to report details, had passed off a second engine at Hatfield and returned with it to the test base at Muroc Lake.

Apart from the mishap just described, the long extension pipe of the XP.80, combined with the hot climate of California, provided a piece of information which was to be very useful later on. The engine ran considerably hotter than in England and the temperature distribution of the static blades was by no means ideal. The observed "hot-spots" were corrected by adjustments in burner flows and led to an investigation which later disclosed a slight air bias from the twin intakes. This had not been noted previously in England, since running temperatures at that time were not high enough to show up the effects conclusively.

Early in 1944 a second and third D.H.100 aircraft became available and with these aircraft and the XP.80 at Muroc, level flight speeds in excess of 500 m.p.h. were attained for the first time, both in this country and in America.

About this time, the U.S. Navy became interested in the Goblin engine for a long-range, naval fighter project. The proposal was to adopt dual power plants by using an air-cooled piston engine driving a propeller for normal operation and augmenting this by a jet unit for combat. A Grumman fighter was converted for experimental purposes and much useful data was obtained on the problem of relighting in the air. Manufacturing arrangements were placed in the hands of Messrs. Allis-Chalmers and a mission was sent to England to study the engine and its fabrication. They entered into the job in a spirit of the closest collaboration and the greatest enthusiasm. Some Allis-Chalmers engines were built and flown but the project was closed down at the end of the Japanese War.

Meanwhile, development in England proceeded apace and experimental engines were next cleared for flight at 2,500 lb. thrust at 10,000 r.p.m. Troubles were encountered and had to be overcome. There were some mysterious failures at the compressor end and a case of fire in flight—fortunately without ill-effects. The original lagging round the jet pipe consisted of an asbestos blanket and this had become soaked with fuel following a false start. It was decided to abandon any absorbent materials for lagging and the shrouded tail with induced air flow was the result. This detail involved quite an amount of work before satisfactory operation was obtained.

A particular development engine completed three 100-hour runs at 2,700 lb. of thrust and by the end of 1944 more than 2,000 hours of testing had been accumulated. Arrangements for production were in hand and in January 1945 the first Type Test Certificate for a gas turbine engine was awarded to the Goblin I at 2,700 lb. of thrust. Meanwhile, the selected development engine had completed between 500 and 600 hours running at this rating.

The next objective was to clear the engine

for 3,000 lb. of thrust and so, at last, to achieve the design figures with reliability on production-built engines. The development of the "flower-pot" combustion chamber not only gave more reliability for the Goblin I but so improved performance that a thrust of 3,000 lb. was obtained at a speed of 10,200 r.p.m. The official type test at this rating was conducted during July 1945 and the engine became known as the Goblin II. Something like 3,600 hours of development had been completed at this time.

The take-off characteristics of the Vampire were so good with 3,000 lb. thrust that modifications were made for trials on an aircraft carrier. Fitted with an arrester hook and additional air brakes, a jet aircraft first landed on and took off from a ship at sea on 3 December 1945 (Fig. 4). For this type of application, a good margin of thrust is required for the "wave-off" condition and acceleration must be above suspicion.

The main stages in the development of the engine are shown in Fig. 5, where the upper line indicates the dates at which special category approval was obtained for experimental flight and the lower line the dates at which these special category ratings were confirmed by formal 100-hour type tests. On the same base is shown the accumulated time spent in development running. The history of the development of the engine is intimately bound up with the growth of knowledge of the functioning of the principal components and something of this story is recounted in the following section.

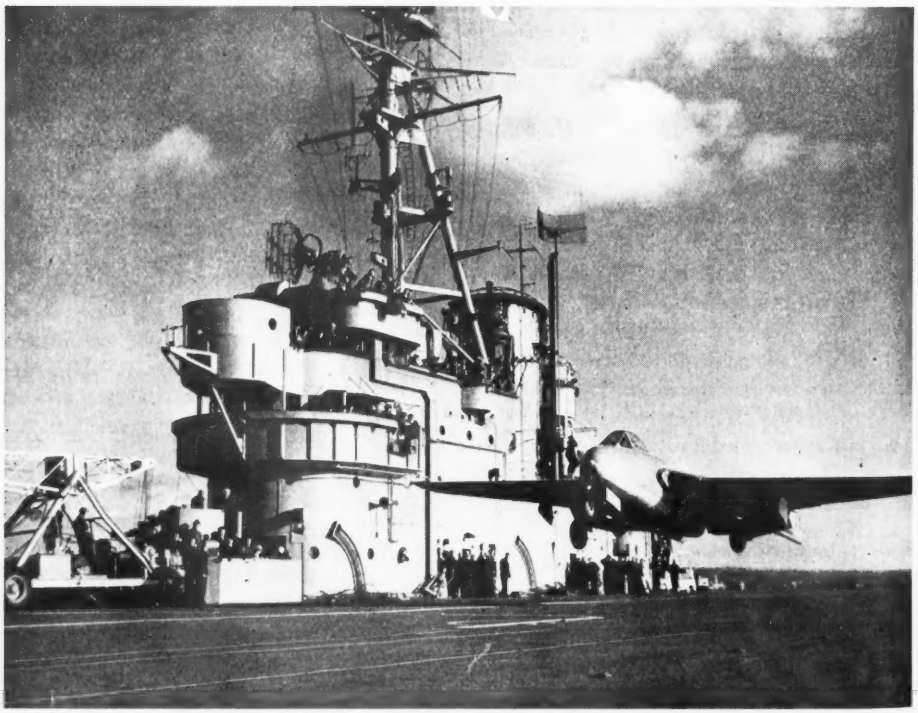

Fig. 4.
Sea Vampire.

4. COMPONENT DEVELOPMENT.

4.1. COMPRESSOR.

During the course of the development of the engine the compressor has remained fundamentally unchanged. It has the same intake shape, the same size of impeller, the same number of impeller and diffuser vanes as when it was designed six years ago. There have been improvements in material and small changes in blade form following vibration studies.

The advantages of gently-curved impeller intake vanes had been demonstrated previously in a supercharger for a piston engine and the results obtained were so good that it was decided to follow the same general conception in the design of the Goblin. Fig. 6 shows the Goblin impeller and it will be noted that the pick-up positions of the impeller vanes curve gently into the radial portions at the tip. This is made possible by machining the curvature rather than by bending the blades from an initial straight form. At tip speeds of the order of 1,500 ft./sec. the velocity of the air relative to the blade at entry approaches the velocity of sound and it is essential for maximum efficiency and mass flow that there is minimum shock at this point. The curvature of the blades of the Goblin impeller is adjusted so that sections of the blade in planes normal to the axis of rotation are truly radial. Thus, there are no secondary bending stresses in the blades from the effects of rotation alone. The loads that arise from imparting angular momentum to the air are negligible from the stress aspect.

The manufacture of the first impellers was a major undertaking and they were, in fact, machined from solid cheeses. These cheeses, which weighed about 500 lb., were the largest forgings that had been made in R.R.59 at that time and some concession had to be given on the properties at the centre. Final heat treatment is completed when the impeller is machined within about $\frac{1}{8}$ in. of

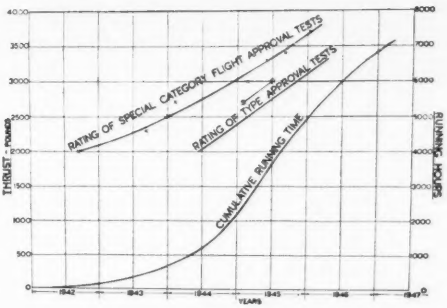

Fig. 5.
Development stages of the Goblin engine.

finished size and the large dimple at the back of the impeller and the hollow boss are beneficial in the quenching operation. As soon as possible, dies were sunk and this step reduced machining and improved properties by increasing the amount of work at the centre of the stamping. The finished weight of an impeller is 109 lb. and the machine used in its production is shown in Fig. 7. Two impellers are machined at a time from a master impeller seen on the right. A combined rotary movement of the work and a fore and aft movement of the cutting head enables the tool to cut continuously round the impeller in a circumferential sense.

In the course of development some impeller failures occurred and, on the advice of High

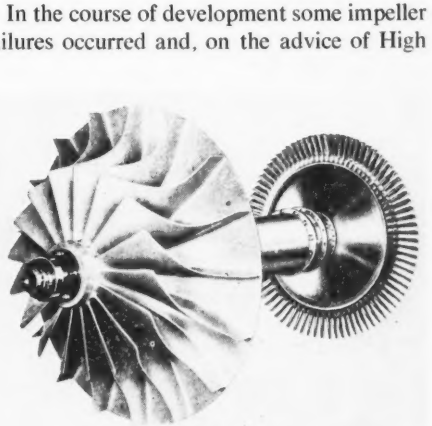

Fig. 6.
Rotor of the Goblin engine.

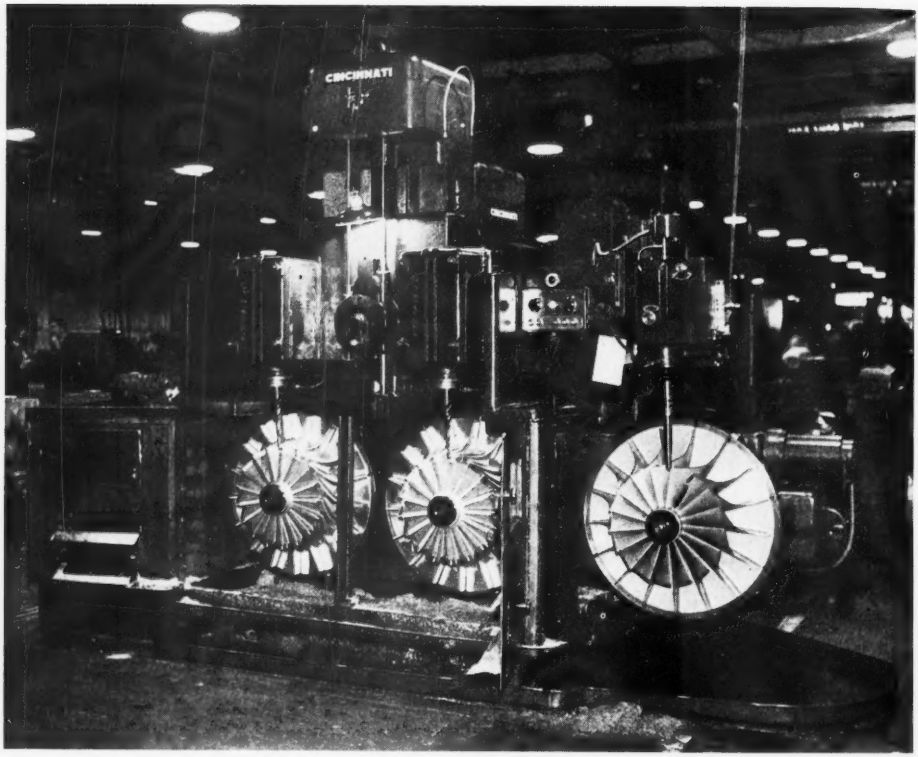

Fig. 7.
Production of Goblin impellers.

Duty Alloys Ltd., a change was made in the alloy whereby the silicon content was controlled to be less than 0.25 per cent. The minimum acceptance properties at any point in the impeller are as follows:—

Ultimate strength	...	24 tons/sq. in.
0.1% Proof strength	...	16 tons/sq. in.
Elongation ...	...	6 per cent.

Considerable importance has been attached throughout to the elongation value as denoting some measure of the ability of the material to relieve itself of internal stresses set up in manufacture and to adjust itself to local stress concentrations at bolt-holes, fillets, and so on. With low-silicon alloy impellers produced from continuously-cast ingots, these minimum properties were handsomely exceeded.

Every impeller is given an overspeed test as a check on soundness. Fig. 8 shows the plant used for this purpose. It consists of a vacuum chamber containing the impeller which, after evacuation of the chamber, can be run up by a motor-car engine to a speed 15 or 20 per cent. in excess of the maximum engine speed. The rig is located in a strong room with remote controls as a safeguard against the possibility of failure.

Some difficulty was experienced with the soundness of the castings for the front casing which were originally made in magnesium. A change was made to aluminium, although it is now thought that the alloy had little to do with the trouble. About this time the surprising discovery was made that it was impossible to cool the rear bearing with hot

air bled from the compressor! The new casting, therefore, embodied an intercooler in the form of a shrunk-in ring or choke, through which the pressure air circulated and was cooled by the main flow of cold air passing into the impeller entry.

The only important change that was made to the diffuser casings was a cutting-back of the 16 vanes at entry to give more radial gap between the periphery of the impeller and the entry to the diffuser. This followed trouble with the combustion equipment caused by high-frequency pulsations in the air flow delivered by the compressor. While this increase of gap was beneficial as far as the combustion equipment was concerned, it was accompanied by a loss of performance and the original design was restored as the engine rating improved.

Another rather mysterious trouble was occasional fouls on the labyrinth seal which invariably occurred during a rapid shut-down from speed. Appreciable axial displacement occurred of the sealing plate relative to the impeller and it was essential both to increase the clearance and to stiffen the plate before these fouls were overcome. Fig. 9 shows the original sealing plate and the current design and indicates the extensive stiffening that was necessary.

The independent testing of the essential elements of a gas turbine of the size of the Goblin is a difficult matter because of the large supply of power that is required. Under the auspices of the M.A.P. and with the help of Power Jets, a spare steam turbine at Northampton was fitted with a gear box and converted to drive a Goblin compressor. The

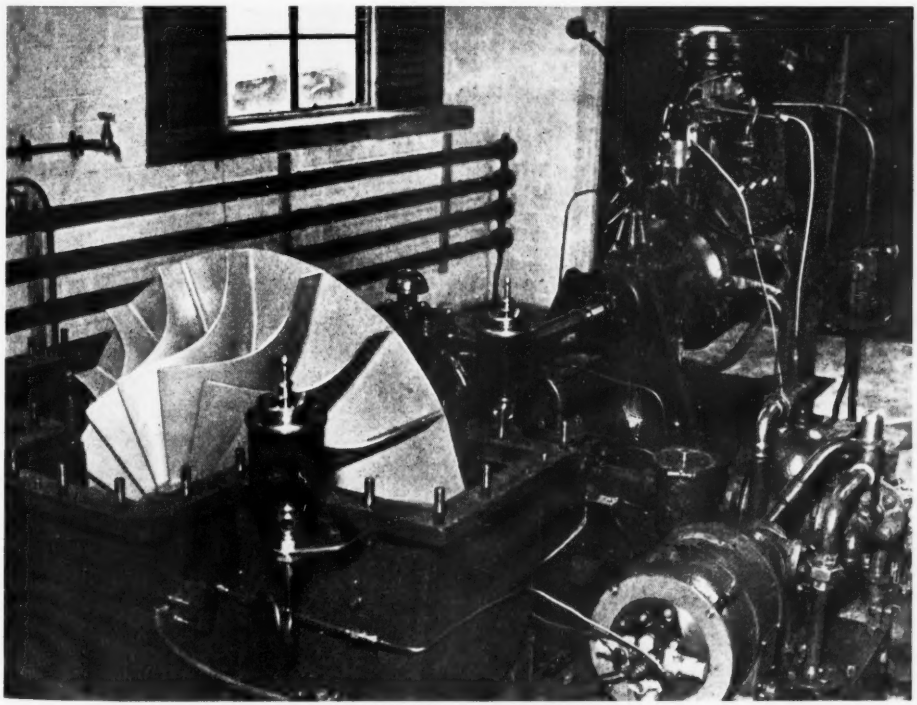

Fig. 8.
Impeller overspeed rig.

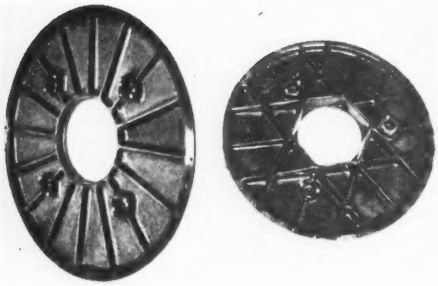

Fig. 9.
Original and strengthened seal plates for compressor.

general arrangement is shown in Fig. 10. The compressor on test was fitted with a reaction stand inside a test cell. Air to the cell could be controlled by a throttle and was measured by a calibrated nozzle in the supply pipe. After passing through the compressor, the air was discharged in a purely radial sense to avoid any effects on the torque balance. With open intake, it was possible to run the compressor at 10,000 r.p.m. before the available 6,000 h.p. set a limit to further increases. A maximum speed of 11,000 r.p.m. was attained with partially closed intake throttle.

Figure 11 is an extract from the data obtained. It shows an isentropic efficiency of 82 per cent. based on the temperature rise and the ratio of static pressures between intake and delivery. The results of these tests have been extremely valuable in making adjustments to the compressor and turbine so that each could work in the region of maximum efficiency. It is unfortunate that the full series of tests were terminated with unexpected suddenness by a rub between the impeller and its casing.

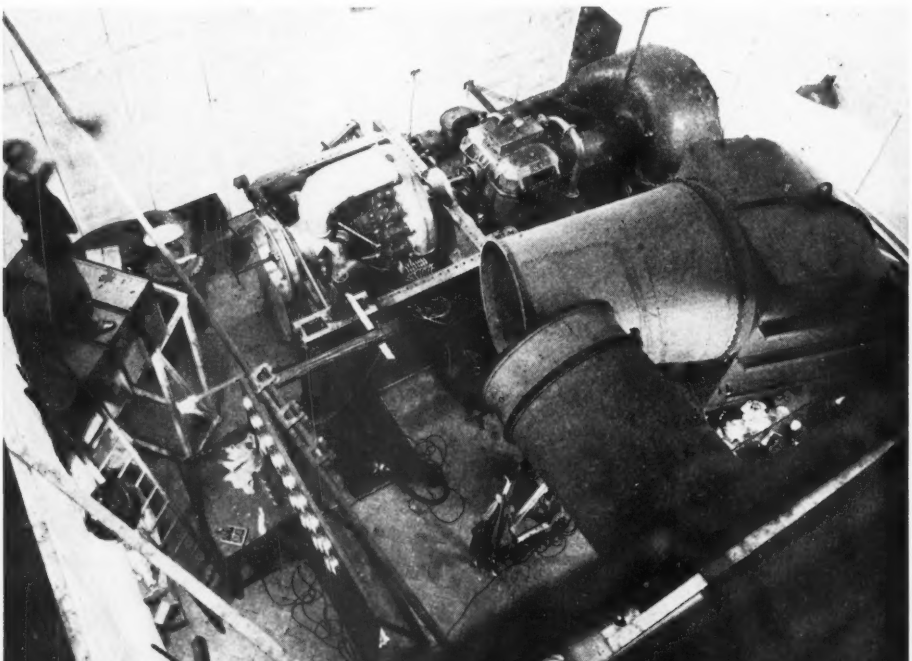

Fig. 10.
Compressor test plant at Northampton.

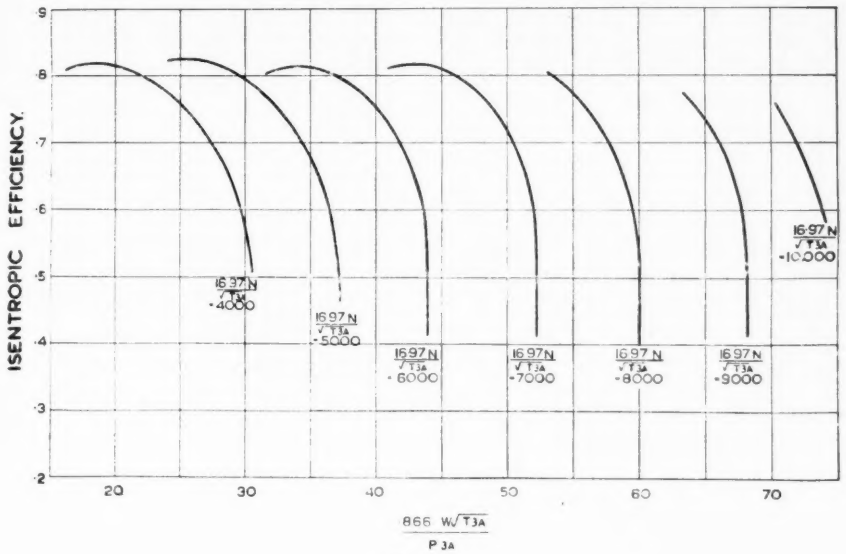

Fig. 11.

Goblin compressor test.—Engine 1001.
Isentropic efficiency based on pressure ratio from eye of impeller and temperature rise.
N=rotational speed—r.p.m. T_{3A}=eye temperature—°K
W=air mass flow—lb./sec. P_{3A}=eye pressure—lb./in.²

More recently, a special study has been made of vibratory stresses in the impeller under operating conditions. For this purpose, wire-type strain gauges have been used and a special technique was developed for cementing them in position in a way that would withstand the centrifugal forces set up at full speed. Slip rings to transmit the electrical impulses at 11,000 r.p.m. have been no easy problem. It has been found that the blades respond to two main exciting frequencies. The first of these occurs at four times engine speed and is associated with the intake arrangement; the second occurs at sixteen times per revolution and is an impulse arising from the shock of the air leaving the impeller and entering the sixteen diffuser passages. Fig. 12 shows a blade failure in fatigue after running for a considerable period on the 4th order vibration. Fig. 13 shows the special slip ring gear for bringing out the impulses from the strain gauge elements.

One result of this special vibration study has been a modification to the impeller which has moved the 4th order excitation outside the running range. By chamfering back the leading edges of the entry portions of the impeller blades, the fundamental flapping frequency has been raised and an unexpected advantage obtained. The modified engine gave increased thrust and a lower operating temperature. This advance is ascribed to an

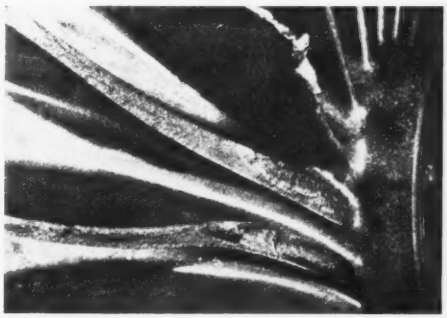

Fig. 12.
Fatigue failure of impeller blades

improvement in the Mach number at the outer portion of the entry vanes, similar to the effects of sweepback in the wings of an aircraft. Since compressibility effects become more serious as speed rises and altitude increases, this discovery may be of considerable help in maintaining overall engine performance for altitude flight.

4.2. TURBINE.

With one important exception, the development of the turbine has been largely a matter of metallurgy. After the first four experimental engines had been built, the chord of the rotating blades was increased by 30 per cent. and their number decreased proportionately. The object of this change was to strengthen the blades by thickening them—particularly at the roots. As a result, the gas bending stress at full duty was reduced from 6.6 tons/sq. in. to 2.8 tons/sq. in. and the natural frequency of vibration was raised. Aerodynamically, the blades were similar to the original narrow-chord type and the performance was, in fact, identical.

One important advantage of the single-entry compressor is that its larger impeller rotates more slowly for a given compression ratio and the slower speed results in a larger turbine wheel to give the necessary blade velocity for good design. A certain gas flow necessitates a certain annular blade area and it follows at once that the blades for a turbine driving a single-entry impeller are shorter than those driving a double-entry impeller of similar capacity. This consideration helps the blade stress situation and has enabled the Goblin engine to run faster and to operate at higher temperatures with an excellent record from the point of view of blade reliability.

Turning now to the metallurgical aspects, the first engines were fitted with turbine blades and discs made from Firth's R.ex.78, the finest austenitic alloy that was then available. Little was then known about operating temperatures and the possibilities of disc cooling. A programme of experiments

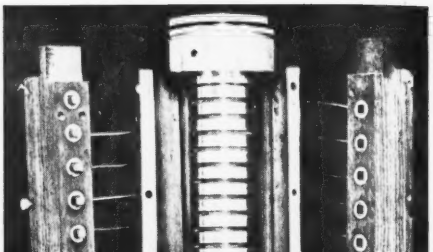

Fig. 13.
Slip ring gear for impeller strain gauges.

with heat-sensitive paints indicated that the disc could be held at temperatures considerably below those of the gas stream and that the centre—which carries the greatest tensile stress—was below 250°C. These considerations, reinforced by theoretical work, indicated that a ferritic type of steel might be used in place of the austenitic material which had been thought essential. A suitable ferritic material offered the following advantages:—

(1) Greater strength in the cool regions and so a lighter construction.
(2) Reduced alloy content and hence cheapness.
(3) Greater ease of forging and machining.
(4) Reduced coefficient of expansion and so reduced temperature stresses.
(5) Greater thermal conductivity and so easier temperature gradients.

The first ferritic discs were made in Jessops' H.3 material—a modified silchrome steel which, after development, became H.3A and was quite satisfactory. An alternative was Hadfields' Hecla 153 which was found a little easier to broach and has been used in the majority of Goblin engines with every

success. The minimum properties required from the disc at room temperature are:—

Ultimate tensile strength	55 tons/sq. in.
0.1% Proof strength ...	40 tons/sq. in.
Elongation	15% minimum

Considerable development work was done by the steel suppliers in both cases and the record of behaviour is such that the early decision to adopt a ferritic material has not been regretted.

The original blades for the Goblin turbine were made in R.ex.78 and it is believed that they were the first blades of any jet propulsion engine to be made from drop stampings. Previously bar material had been used but the stampings saved material and machining time and gave at least some sort of grain flow from the blade proper into the root. At a later stage, experiments were made in stamping blades to the finished size but it was found that most of the time saved in machining was occupied in making the dies which had a very short working life. Moreover, it was decided that it was important to remove .020 in./.030 in. from the surface of the stamped blade in order to eliminate all surface defects.

Altogether, something like 1,400 hours of development running were completed with R.ex.78 blades before increased engine ratings and improved availability of the new material made advisable a change to Nimonic 80. Incidentally, there has been only one failure of a Goblin blade in flight, and in this case the pilot throttled back slightly and continued flight for about ten minutes before landing safely at his home aerodrome. This was really a welcome piece of information, since the centrifugal force set up by the loss of two-thirds of a blade amounts to about 2,500 lb. weight at 10,000 r.p.m. and there were real doubts about the behaviour of the engine mounting and the effects of vibration under these circumstances.

The static turbine blades were also in R.ex.78 originally. Later they were changed to G.17 and then to G.18 or Nimonic 75. These last two materials have given very little trouble and constitute the present standard. Surface finish of blades is an important consideration from the point of view of inspection for soundness and segregations. The de Havilland Company have designed and built a number of fatigue machines in which an actual blade may be subjected to a steady bending moment on which is superimposed a fluctuating bending effect. A fatigue test may be run at room temperature or at an elevated temperature. The excellent record of blade reliability in the Goblin engine is ascribed in part to the modest initial stresses and in part to the attention given to inspection and finish during manufacture.

4.3. Combustion chambers.

While the fundamental design of the compressor and turbine have remained more or less fixed during the life of the Goblin, the same cannot be said of the combustion equipment. Before an engine ran, something like 90 modifications had been made in the space of nine weeks testing on a rig and research and development has been continuous ever since. The total number of chambers has remained at sixteen and the length available between compressor outlet and turbine inlet has been kept constant; almost every other factor has changed at one time or another. Fig. 14 compares the current production chamber with the design originally employed. A simple "flower-pot" flame tube replaces the original stub-tube design and a deep-drawn outer casing with cast head is now substituted for the rather complicated original design with expansion bellows and a multitude of welded joints. Both are of the straight-through type.

The factors influencing combustion chamber design, as in most things, are conflicting. From the aspect of performance, the loss of total pressure between entry and exit

should be a minimum; mixing should be perfect so that a gas of uniform temperature and velocity is delivered to the turbine; flame length should be short in order that overall dimensions are not excessive. Short flames and uniformity of delivered gas go with good mixing and good mixing is helped by high pressure drop. Early chambers with stub pipes to distribute the diluting air owed their success — in a chemical sense — to good mixing, but pressure drops were high and reliability poor. Later, research work at the Imperial College of Science showed that intimate mixing of two gas streams could be improved by a sudden enlargement at the point of introduction of the secondary stream. The Lucas "flower-pot" design utilising this principle was first developed for the Goblin and constituted an immediate step forward.

Some loss of total pressure is inevitable in a combustion system but the early chambers offered obstructions which in no way helped the mixing process. A progressive removal of these obstructions and a streamlining of the flame tube and its casing have led to a better diffusion of the air leaving the compressor and to an appreciable reduction in the overall losses.

The mechanical side of combustion chamber design was neglected by all for too long. Looking back, much trouble might have been saved by more robust design and by a better appreciation of the working conditions. The following cardinal points have emerged: —

(1) Projections into the flame (stub pipes, chutes, and so on) are to be avoided. They will fatigue in vibration and they will be burnt by the hot gases.

(1) Flame impingement on any metal surface will cause trouble either by direct overheating or by differential expansion effects which will produce buckling and cracks.

(3) The flame tube must be well-supported but left free to expand in all directions from the points of location.

(4) Welding should be as little as possible and as good as possible. The same material should be used throughout for a welded component.

(5) The air flow must be properly organised and as symmetrical as possible. This applies particularly in the primary zone where any bias will give local variations in mixture strength, hot spots and carbon form-

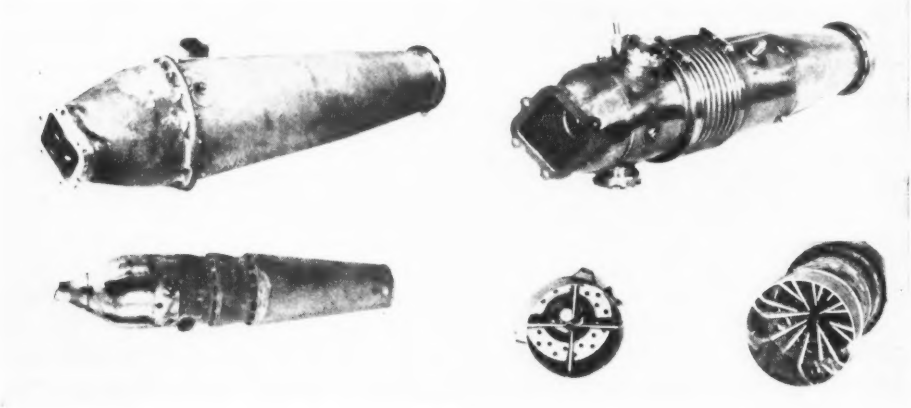

Fig. 14.
Comparison of original and present combustion chambers.

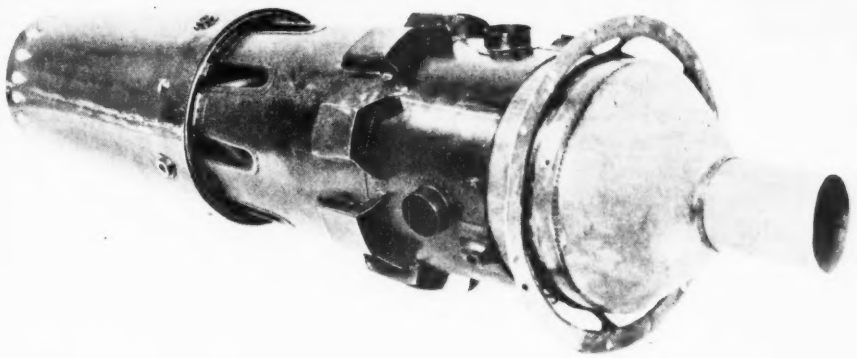

Fig. 15.
"Daisy" combustion chamber.

ation. Dilution air can be used to isolate and cool hot metal surfaces—but only if it flows evenly over these surfaces.

By way of example, Fig. 15 shows the internals of the "daisy" chamber which in its original form offended nearly all the foregoing precepts. It had daisy "petals" and chutes projecting into the flame: they quickly burnt away. The flame impinged on the outer casing after leaving the mixing section and a muff was added. Expansion problems were plentiful because of the mixture of hot and cold parts. Primary air entered one side of the large swirler and came out on the other. A "chimney" was necessary before steady combustion was obtained. This chimney was the precursor of the streamlined entries for the primary air of present-day chambers. On the engine, the daisy chamber was never a success, but it taught a great deal.

Combustion chamber testing is now an accepted practice (Fig. 16) but it has limitations and the final criterion can be established only by actual engine running. This is because no simple rig can imitate exactly the flow conditions occurring in an engine. Moreover, the durability of a chamber on a rig is entirely misleading, partly because the air flow is not representative but mainly because a rig lacks the pressure fluctuations which occur in an engine due to the high frequency impulses from the vanes of the impeller.

Vibrations set up by these pressure fluctuations can be very destructive to the metal parts at the entry to the combustion system and were behind the decision to change from sheet metal to cast aluminium for the front outer casings (Fig. 14) on the Goblin.

One cannot conclude this section without grateful acknowledgment of the continued assistance rendered by the Lucas Research Organisation in the development of an efficient combustion system.

4.4. Fuel system and starting.

The first runs of the Goblin were made with spring-loaded burners which opened their ports as fuel flows increased. This provided a good fuel pressure for idling without excessive pressure at full duty. The moving parts of the burner were likely to stick occasionally and the individual combustion chambers could then go out of balance. To avoid this difficulty it was decided to adopt simple fixed-orifice burners

and the first Goblins flew with this arrangement. A burner pressure of 800 lb./sq. in. was horrifying at first, but it worked quite well after some initial trouble with pipes and joints and there remained sufficient pressure at low flows for good atomisation at reduced r.p.m. and when flying at altitude.

Figure 17 is a diagrammatic representation of the fuel system as currently employed. Fuel from the tank passes to a control box where the pressure is determined by an altitude-sensitive relief valve or "barostat." A tapered needle connected to the pilot's throttle determines the drop from the datum set by the barostat to the pressure required in the burner ring. The tapered needle is calibrated so that the pilot's lever responds to thrust rather than to r.p.m. The barostat ensures that changes of altitude produce no sudden changes in r.p.m. and that the sensitivity of the pilot's lever is maintained. A mechanical overspeed governor is placed between the throttle and the burner ring as a safeguard, but is inoperative for normal working. For starting, fuel is initially stored in a hydraulic accumulator which is released automatically by the starting valve when a critical pressure is obtained. Drain valves and an on/off cock are provided for shutting down.

A piston type of fuel pump was selected because of the pressures involved and a modified version of the Dowty hydraulic pump proved very suitable. The change to kerosene from hydraulic fluid rendered lubrication more difficult and troubles were

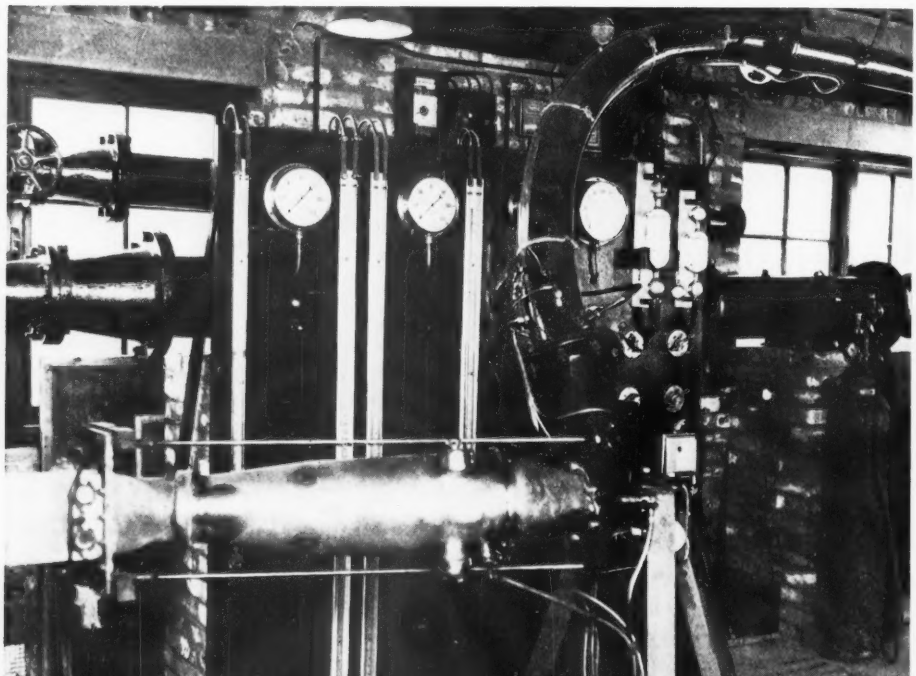

Fig. 16.
Full density combustion test-rig.

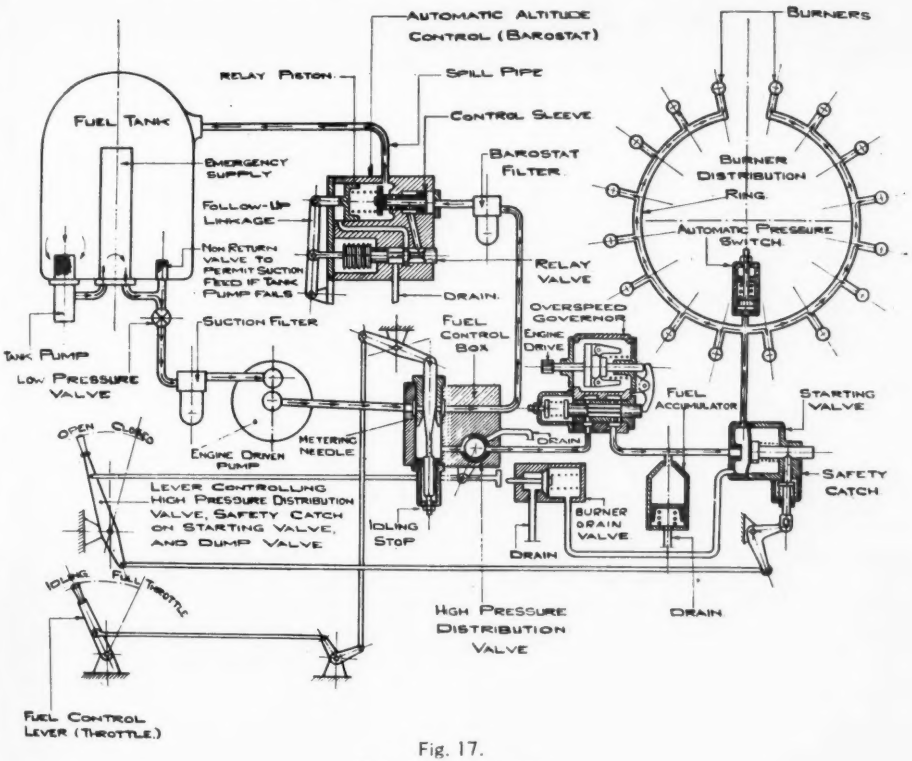

Fig. 17.
Fuel system diagram.

experienced at first with the pistons, slippers and centre bush. Active development over a number of years has resulted in a pump which now runs the full overhaul life of the engine at working pressures of over 1,000 lb./sq. in. The principal changes in the pump have been alterations in materials and adjustments in working clearances to suit the new conditions of operation.

At first, starting was accomplished by motoring the engine at 800/1,000 r.p.m. and manipulating the various fuel controls by hand. Good starting could be obtained by a skilled operator and vice versa. The introduction of the "controlled overdose" of fuel from the fuel accumulator synchronised with the introduction of the Rotax panel which made automatic the different electrical functions. When the starter button is pressed a clock mechanism is wound up and the subsequent events take place in a timed sequence. First the starter motor pinion is gently engaged and then the current increased to a value which is the safe limit for the motor and the starter mechanism. As speed increases, a final resistance is removed and the engine accelerates to its self-driving speed. Meanwhile the ignitor plugs have been in operation so that ignition takes place as soon as the starting valve and accumulator give a puff of fuel from the burners. Should the engine fail to start within 30 seconds, the electrical circuits are broken and the engine comes to rest.

5. TESTING.

The testing of gas turbine engines presented new problems in the measurement

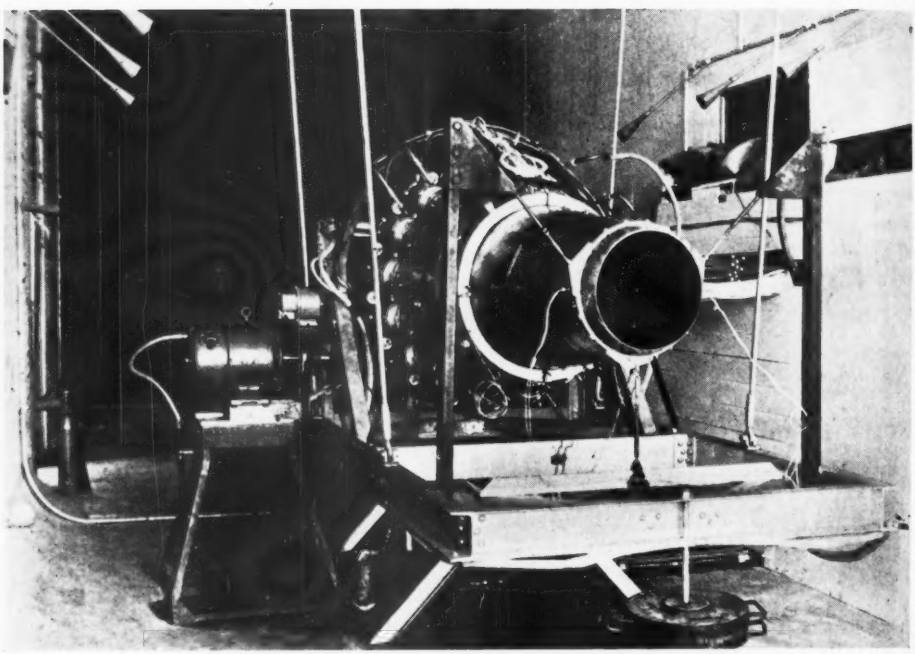

Fig. 18.
Suspended test-bed with prototype Goblin.

of thrust, the accurate recording of speed, the measurement of air flow and the disposal of the exhaust. Fortunately, however, the bare essentials were straightforward and it was possible to convert two propeller tunnels intended for Gipsy piston engines in time for the completion of the first Goblin. Fig. 18 shows the prototype engine in one of these tunnels. The engine was mounted on a cradle suspended from the roof by four hinged rods. Movement of the cradle in a forward sense was prevented by a hydraulic plunger which transmitted its pressure to a gauge in the test cabin as a measurement of the thrust being produced. The large motor alongside the engine was a temporary means of cranking the engine to determine its starting characteristics.

A great deal of testing has been completed in these converted tunnels but they are noisy and unnecessarily large. A more modern type of bed used for production testing is shown in Fig. 19 (reproduced by courtesy of *Flight*). In this case, the engine is mounted on a trolley running on a special ball-bearing arrangement below floor-level. This facilitates engine changes and improves accessibility. Thrust is recorded hydraulically, as already described, and the jet passes through a silencer or de-tuner mounted inside the sound-proofed exhaust tunnel. A bell-mouthed air intake is used as a measuring orifice and is mounted on the engine so that true net thrust is recorded. Comparative data have been obtained between these test bed intakes and the different types of aircraft intake. The most reliable method of recording speed has been by the use of a stroboscope driven positively by the engine on test and illuminated by a flashing neon lamp operated by a precision tuning fork. Because the thrust/speed characteristic is steep at

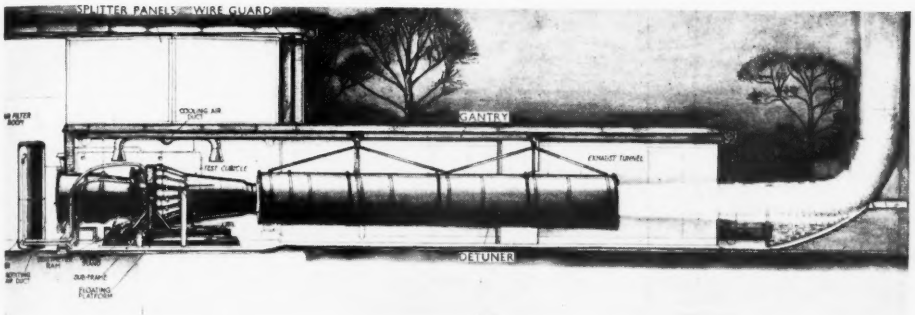

Fig. 19.
Production test-bed layout.

full duty, it is essential to measure r.p.m. with far greater precision than suffices with a piston engine.

Goblin engines have been tested in Arctic chambers at $-40°C.$ and in tropical chambers at $+40°C.$ Generally speaking, the gas turbine is more amenable to extremes than its piston counterpart. An important consideration, however, is the loss of performance in hot climates which arises from the reduced mass flow and the adverse effect of ambient temperature on critical temperatures throughout the engine.

One of the most interesting calibrations of the Goblin engine was made at the end of the war in the B.M.W. altitude test cell at Munich. Fig. 20 shows the Goblin engine in the test chamber, which was 12 ft. in diameter and could be evacuated to pressures equivalent to 50,000 ft. altitude. The supply of air to the intake could be regulated from a very low speed to a blast of 550 m.p.h. and could be refrigerated to $-70°C.$ if required. A diagrammatic representation of the plant is given in Fig. 21, which shows pressures and temperatures at different points in the circuit. In brief, air is compressed in a compressor and cooled in an arrangement of heat-exchangers before passing to an expansion turbine ahead of the altitude chamber. By adjustment of the flow through this turbine the temperature of the air entering the cell may be varied between limits of $-70°C.$ and $+50°C.$ The blast equivalent of the speed of flight is obtained by regulation of the compressor supplying the cell in relation to the air consumption of the engine and the capacity of the exhauster pumps

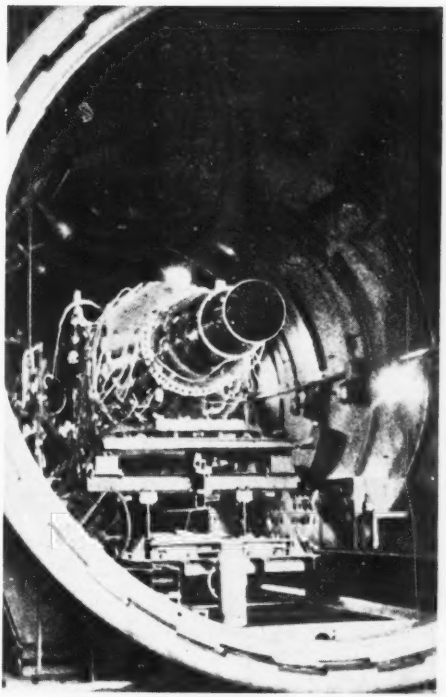

Fig. 20.
Goblin engine in altitude test cell at Munich

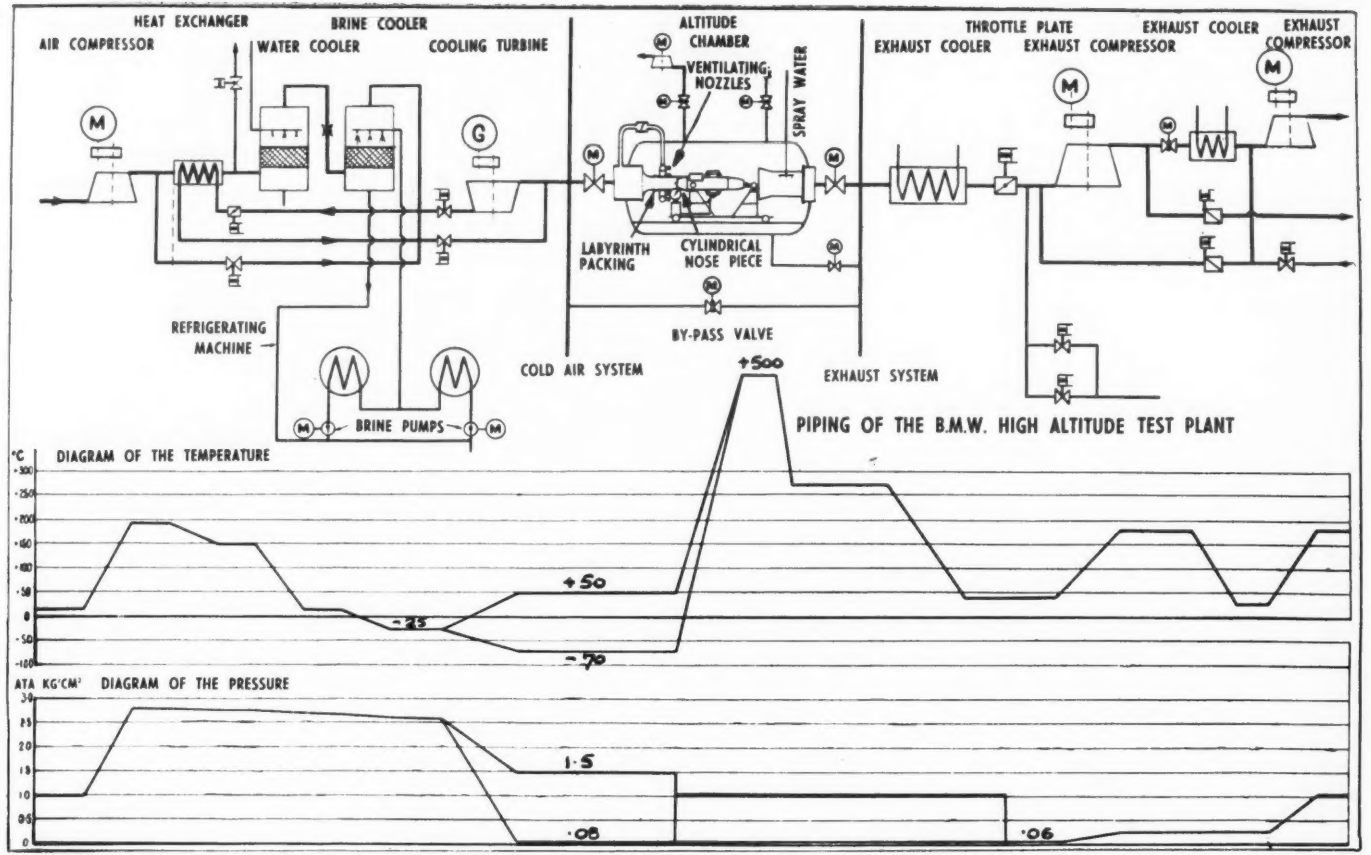

Fig. 21.
Diagrammatic arrangement of Munich plant.

which evacuate the altitude chamber. The exhaust from the engine is cooled by water spray and in heat-exchangers before it is re-compressed to atmospheric pressure and discharged.

Altogether, over 70 hours of testing were completed at Munich in the course of a few weeks and information was obtained which no amount of flight testing could provide. Not only was the speed of testing much better than in the air, but the engine could be fully instrumented and the variables affecting performance adjusted and explored independently. Fig. 22 is an extract from some of the results and shows the change of net thrust as affected by ambient pressure (P_a), ambient temperature (T_a), speed of rotation (N) and forward speed (V_a). The curves are strictly non-dimensional but the constants have been chosen so that the values are appropriate to sea-level conditions ($P_a = 14.7$, $T_a = 288°K.$).

At the lower speeds of rotation, net thrust is not greatly affected by forward speed and, in fact, falls off because of the adverse momentum change at the air intake. At maximum r.p.m. this fall-off is more than recovered by the beneficial effects of ram in increasing the mass flow through the engine. At the highest speeds of flight, the engine is considerably more powerful than its nominal 3,000 lb. thrust on the test-bed would indicate.

The results of these tests have been of great value and there is no doubt that the present lack of altitude test equipment similar to the Munich plant is a serious handicap to the progress of gas turbine development in this country.

6. CONCLUSION.

How far it is possible to continue the development of a particular gas turbine engine depends intimately on likely improvements in metallurgy and the technique of cooling. As will be seen from Fig. 23, the curve of temperature rises steeply at full

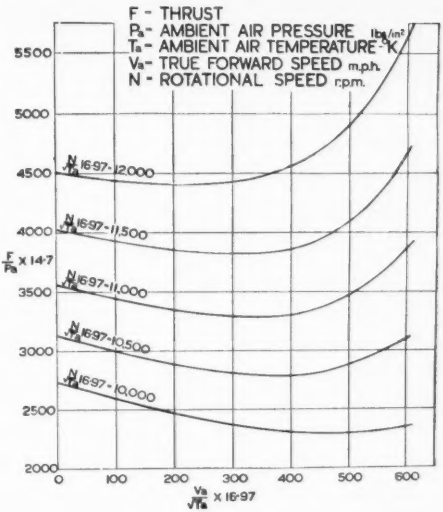

Fig. 22.
Goblin engine No. 1009
Calibration on B.M.W. altitude test plant.
Thrust versus forward speed.

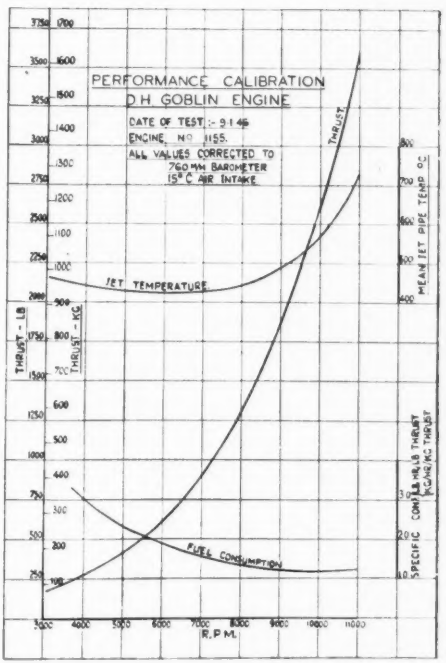

Fig. 23.
Performance curve of Goblin engine.

Fig. 21.
Diagrammatic arrangement of Munich plant.

Fig. 24.
D.H.108 aircraft.

speed and the ability of materials to withstand increasing temperatures without fatigue or appreciable creep, sets a limit as to what can be done. In this connection it should be remembered that improvements in materials can be used to give better reliability at a given duty or an improved rating for a given reliability. Jet pipe temperature is very much the boost gauge of the gas turbine engine; there is an immediate response to an increase, provided that the internals of the engine raise no objection.

The development of the jet propulsion engine has advanced aircraft speeds by over 200 m.p.h. in the past six years and has brought new problems to the aircraft designer. Further increases in thrust are unlikely materially to increase speeds in level flight, unless the effects of compressibility can be overcome. This will involve work for both the aircraft and the engine designers and the closest collaboration is necessary. One such attempt is shown in Fig.24 which depicts the D.H.108, an experimental tailless aircraft with swept-back wings and an uprated Goblin engine. The performance is considerably better than that of the Vampire.

In a paper of this type, it is manifestly impossible to do justice to all the work that has gone into the development of the Goblin engine. Six years of intensive work by some hundreds of people cannot be compressed adequately into the space of a few thousand words. It has been impossible, for example, even to touch on the manufacturing aspect which—and particularly in its earlier stages—involved problems and methods of improvisation just as interesting as those here described.

Grateful thanks are due to the Ministry of Supply and to the de Havilland Enterprise for permission to publish the work described in the paper and to the author's colleagues of the de Havilland Engine Company for their assistance in the preparation of the essential data.

DISCUSSION

Dr. H. Roxbee Cox (Director, National Gas Turbine Establishment, *Fellow*): The early history of jet propulsion in this country was really the history of three great engines and three great aeroplanes; the engines were the Whittle, the de Havilland and the Metropolitan Vickers jet propulsion gas turbines; the contributions of other famous companies, whom they all knew, came rather later in the chronology. The three great aeroplanes were the Gloster E.28/39, the Gloster Meteor, and the de Havilland Vampire. It was interesting to note that the three engines all took the air in the prototype Meteor which in those early days was called the F.9/40.

The Whittle and the Metropolitan Vickers engines had been described and their development had been traced before the Institution of Mechanical Engineers, and he thought they were fortunate in having heard about the development of the third of those pioneer engines from the chief engineer of the de Havilland Engine Company.

Mr. Carter of the Gloster Company had spoken about two of the aeroplanes he had mentioned and he hoped that, following the example of the famous demonologist, Father

Montague Summers, Mr. Bishop of the de Havilland Company would soon give a paper on "The Vampire, his Kith and Kin," which would be complementary to that which they had just heard from Mr. Moult.

The lecture was an occasion, and probably the first the Society had had, on which they could congratulate the de Havilland Engine Company on the extremely fine work which they had done in the past few years and which had led to the engine which Mr. Moult had described.

Mr. F. Pilling (Metropolitan Vickers, *Associate Fellow*): There was one point he would like Mr. Moult to develop in more detail—his remarks on the acceleration of the engine when the Vampire was flown from a carrier. Most of them knew that the acceleration time of the jet engine was rather a thorny problem. The operational people wanted the jet engines to accelerate to maximum r.p.m. almost before the pilot had touched the throttle.

It would be interesting to hear what Mr. Moult had done in that aspect.

Mr. Moult: Acceleration when operated from a carrier was one of the features of the enlarged air brakes. When the pilot approached the carrier he applied his brakes and therefore had to keep the throttle fairly open. Instead of landing at 4,000/5,000 r.p.m., as he would if it was a normal Vampire, he found he had to keep up to 7,000 r.p.m. The pilot, therefore, had a margin of thrust available, because he could both accelerate the engine quickly if he got into a jam and simultaneously retract the air brakes. The emergency get-away was, in fact, quite satisfactory.

They had done their best to improve the acceleration of the engine and from a normal idling speed of 3,000 r.p.m. to the full speed of 10,000 or 10,500 r.p.m. occupied perhaps seven seconds. The rate of acceleration at the higher speeds was much improved and it would be possible to go from the carrier approach speed of 7,000 r.p.m. to full thrust in about two seconds.

Dr. H. Roxbee Cox: He agreed with Mr. Moult about the need for altitude plant. They had nothing like the Munich plant, which was no longer available to them. As soon as possible they would have adequate altitude test plant here, although he feared its completion must still be several years hence.

Mr. Moult had said that the engine had not changed much during its life. That was a remarkable thing. They had there an example of an initial conception which really remained unaltered as regards its main features through the whole of its life. The engine did not look much different now from the first day he had seen it, although internally there might be a little change.

Was the device called a "thrust spoiler" of value in dealing with a baulked landing on a carrier? The matter had been raised at the conference on the previous day, but would bear mention again. He would be interested to hear views about it. The thrust spoiler could be operated in one second. So that if a pilot came in with the thrust spoiled, failed to land, and wished to make another circuit, the full thrust was available in one second.

Mr. Moult: He had not been present at the conference on the previous day and what he said might be contrary to the findings of that meeting. They had discussed the point with the de Havilland Aircraft Company and had come to the conclusion that, although they liked the thrust spoiler, those they had seen were rather heavy and had not been too reliable. What was wanted was a negative thrust device and if a reliable variation of it could be developed it would have a wide application. Once the aeroplane was on the deck, the arrester gear seemed most effective.

The Munich plant had been of great assistance, not only in determining performance, but in combustion problems. Windows

were fixed on top of the altitude cell and through these windows and corresponding windows in the combustion chambers it had been possible to observe the flame under altitude conditions. The Lucas Company took samples of gas from inside the jet pipe and flame tube and obtained much data on combustion at altitude. It was a most useful piece of work and was subsequently extended by Rolls-Royce Ltd. using a Derwent engine. In about 70 hours of running, the de Havilland team took over forty thousand observations which they were still analysing!

Air Commodore D. F. Lucking (*Fellow*): He would like to know more about the operation of turbo-jet and propeller-jet engines on the ground. The problem of acceleration had been mentioned and the associated problem of deceleration. If they had half a dozen of the propeller-turbine aircraft on a congested perimeter track there might be trouble in manœuvring and getting the engines to answer the throttle as quickly as piston engines. He thought it might be a difficult problem, particularly in the case of those turbines which had two turbines, one driving the propeller and the other driving the compressor; possibly their response would be quite different.

Mr. Moult: He could not give much help in that matter because, as he was an engine man, he was not very knowledgeable on ground-handling problems applying to numbers of aircraft, but he did not think that there was any fundamental barrier. His experience was confined to pure jet engines which manœuvred quite well. There was no difficulty in parking the aircraft, but the jet effect had to be watched when manœuvring the aircraft close to one another. The danger from the engine exhaust would be less with a propeller-turbine but, in addition, there would be the normal slip-stream effect.

He understood that the throttle response of the propeller gas-turbines had been excellent on the ground and, although it would be different with different designs, he had no major misgivings on this score.

Mr. R. S. Stafford (Handley Page Ltd., *Fellow*): Had the lecturer any thoughts on the use of compressors for jet engines as a means of supplying air for pressurised cabins? He had viewed with envy the large quantities of air handled by the compressors of the jet engine, and he thought it occurred to most designers at some time or other that here was a golden opportunity of cutting out at least one piece of equipment. He had sounded jet designers and there seemed to be a reluctance to spare some of the large quantities of air that their compressors were handling for the purpose of pressurising the cabins. The Americans were believed to be quite favourable to that method.

Had Mr. Moult strong views on the matter and did he realise that with jet-propelled aircraft they would be able to dispense with a separate cabin blower?

Mr. Moult: They had no very strong feelings in the matter. Their engines were fitted either with a cabin blower or with a manifold which could bleed air from the main compressor and take it off for cabin pressurisation. There was, however, a growing feeling against bleeding, mainly for reasons of contamination. They could not guarantee that there was not the slightest trace of oil or fuel vapour in the air and in a civil transport such contamination had to be avoided. Another drawback was that if they bled the main engine then they were dependent on the r.p.m. of that engine for the pressure supply. If the main engine were throttled, the available pressure was reduced and might be insufficient at altitude. On the other hand, with a separate blower the cabin pressure could be more independent of the engine speed.

Power was necessary to pressurise a cabin and the process cost fuel whether a separate blower was used or the main engines were bled. It was unlikely that a more efficient compressor could be used than the main

engine, but there might be secondary effects which made " bleeding " undesirable.

Mr. F. Pilling (*Associate Fellow*): He did not want to start a gas-turbine discussion, but Mr. Moult had not been firm enough with Mr. Stafford. They knew that an aircraft designer's ideal aero-engine was one which, for a given horsepower, had no weight, no bulk and consumed no fuel.

Where jet engines were concerned the aircraft designer noted that 100 tons of air were consumed in one hour, why then could he not take a few pounds of this each minute for cabin pressurisation? But this "small" quantity of air was required at high altitude and must be maintained even at idling r.p.m. conditions when the mass flow through the engine could be less than one eighth of that already quoted and the compressor outlet pressure insufficient for the purpose.

Similarly, on hearing that at take-off the turbine delivered a maximum of 6,000 h.p. to the compressor, he immediately argued that a mere 100 h.p. or even 200 h.p. diverted to drive aircraft auxiliaries would not be noticed. But again, these services were necessary at idling conditions at high altitude where the total power output would be considerably reduced.

Worse still, from the engine designer's standpoint, was the assumption that neither of these services should increase the fuel consumption and he appealed to the aircraft designers not to expect the jet engine to drive the aircraft and all their little gadgets and still consume no fuel.

Mr. W. R. Farr (*Graduate*): When an engine operated in a sand-laden atmosphere, it would obviously be most undesirable to have a filter in the air intake. How would turbine blades stand up to operation under these conditions?

Mr. Moult: While information was limited, it could not be claimed that sand was good for a jet engine. On the other hand, it was surprising what quantities of dirt and dust had been passed through their engines without doing serious damage. When the tests were run at Munich, the air came from an area of severe bomb damage and pounds of brick dust were inhaled. The engine ran on successfully, although it was very dirty when stripped and the leading edges of the compressor blades were pitted. An axial compressor was more susceptible to dirt than a centrifugal machine and there was a corresponding drop in performance. Unfortunately, complete filtering was out of the question for the large quantities of air involved.

A deflector might be used for take-off from sandy aerodromes but the full benefits of ram should be available by retraction of the deflector at the higher speeds of flight.

Mr. A. W. Morley (*Associate Fellow*): Swept-back wings would allow an aircraft to fly at speeds more nearly approaching the speed of sound and he wondered if, in the jet-turbine engine where the speed of the gases must reach almost the speed of sound, the same principles of the swept-back wing could be used. He thought they would apply particularly to the entry to the diffuser of the centrifugal compressor and possibly to the turbine. Had this been considered, and had any research been done along these lines?

Mr. Moult: The modification to the impeller to improve vibration characteristics had been, in effect, a mild degree of sweep-back of the pick-up vanes and had resulted in better thrust and cooler running. They were now trying to exploit the idea further and he did not know how far they could go. The velocity of the air relative to the blades was high and the beneficial effects were understandable at full duty.

Diffuser blades had also been chamfered at entrance—not to increase performance but to break up the shock wave which was so harmful to the combustion equipment. Here again the Mach No. was high.

Mr. C. M. Barter (*Associate Fellow*): There was one point in the development of

the engine which Mr. Moult did not seem to have brought out, and that was the form of the burner itself, as distinct from the combustion chamber. He would like to know more about whether the direction in which the fuel was sprayed into the chamber made a lot of difference and whether it wanted breaking up into several separate jets and so on.

Mr. Moult: He did not think he could give a scientific statement. Atomisation was important. Fuel was admitted to a swirl chamber in the burner through tangential holes and was then sprayed out conical fashion in a fine mist. The difficulty of maintaining the mist was that at sea level the fuel pressure was perhaps 1,500 lb. per square inch, but at altitude that pressure might drop to 25 to 30 lb. per square inch. To provide for those two extremes of pressure and maintain a fine atomisation was a problem.

The general idea was to produce fine atomisation and so short flame, but it did not seem to matter whether the fuel swirl was right-hand or left-hand in direction. Cone angle affected atomisation as well as impingement on walls, igniter plugs, and so on. There was also an organised air swirl about the burner which helped the mixing process and provided a backward flow of air feeding the burner and maintaining stable combustion in the primary zone.

Major F. B. Halford (de Havilland Engine Co. Ltd., *Fellow*): There were one or two points in connection with spoilers that he would like to mention. From the aircraft point of view the spoilers were likely to be fitted on the end of the jet pipes and were therefore not part of the machine. All their air designers were producing aircraft which were tail heavy, so that if the engine men wanted to put anything on the end of the tail pipe it was naturally resisted. Until the spoiler became part of the original engine it would not be popular.

So far as component testing was concerned, it was always amazing to him that so many firms had got so far with the gas turbine without any facilities to do any proper component testing. He envied the steps which had been taken in America to press for that equipment for full-scale testing. They suffered here from not having that plant. In a few years they might have those facilities, but he did not think they would do justice to the gas turbine until they were available to the firms who were developing the engines. It was like flying blind. They had no means of testing the turbines and compressors under really full-scale conditions. If it had not been that at Munich the Germans had been more far sighted than they had been, that the war ended when it did and that they got to Munich before the Americans, they would not have got the results that they had and which were so valuable.

Mr. T. G. G. Newbery (*Associate Fellow*): One of the features of the Goblin was the single-sided impeller with the high velocity intake, which was quite the opposite of the Whittle with its plenum chamber. Could Mr. Moult tell them what was the efficiency of the high velocity intake and whether it varied with forward speed? Also, whether that type of entry was adopted as part of the overall aircraft design, or because it was considered to be more efficient than the other type?

Another feature of the engine was the straight-through flow, from the entry straight through to the exhaust. That struck the plain engineer as being the logical thing to do, rather than, as on the Whittle, to reverse the flow half-way through the process.

Did the lecturer consider that contributed to the overall efficiency of the engine?

Mr. Moult: It was difficult to quote an exact figure for intake efficiency, but in the case of the Vampire it would be in the region of 90 per cent. That was to say, of the free-stream total head they retained about 90 per cent. at the entrance to the impeller. They considered it important to have an efficient

duct system. They were dealing with an air-flow engine and the fewer times they changed the direction of flow or unnecessarily slowed it down, the better it was for the overall efficiency. In choosing the single entry blower, they were governed very much by the desires of the aircraft designer. He did not want big openings in the wings, but preferred high velocity intakes and direct ducting to the impeller. Experience with a reciprocating engine had shown that it was possible to design a better and more efficient single entry compressor than the earlier double entry types. They had never regretted the single entry decision; it had led to a lot of advantages and the faster they went and the higher they flew the more apparent these advantages became.

As to the combustion chamber arrangement, this was an early choice. It seemed the proper thing to take the air in at one end and out at the other. That led, he was sure, to reduced losses and more uniform velocities. Initially some advantage was lost in that it was not possible to draw directly on the experience of Power Jets with their reverse-flow combustion chambers. But further experience had shown that for the type of engine under consideration, straight-through flow was correct. The same thing did not necessarily apply to different types of engine, where combustion intensity was not so high and questions of convenience could outweigh the obvious choice on aerodynamic grounds.

Dr. E. A. Watson (Joseph Lucas Ltd.): He could not add much to what Mr. Moult had already said on the straight-through engine. In deciding on a straight-through design the de Havilland Company undoubtedly took a certain risk as, up to that date, all experience was on the bent type. He understood that Air Commodore Whittle had at one time considered the use of straight-through combustion but had decided against it on account of the difficulty which he anticipated would arise from the uneven air distribution at the entry. That difficulty had, in point of fact, been one of the major problems which had to be confronted in developing a straight-through engine. It was not until the necessary instrumentation had been devised for exploring the air distribution over the compressor outlet and the combustion chamber inlet that it was possible to design and manufacture straight-through combustion chambers, with a certainty of getting freedom from distortion and a satisfactory working life.

Mr. Moult had shown in one of his illustrations a protuberance on the end of the combustion chamber which he had called a "snout."

This "snout" formed the inlet for the combustion air to the combustion zone and the exact siting of the zone with relation to the air stream was extremely important as it was necessary that it should collect air from that section of the air stream where the velocity was as nearly as possible uniform.

It was to the credit of the de Havilland Company that they had faced up to unknown problems and had succeeded in producing what they had promised. Mr. Moult had mentioned their forecast of a thrust of 3,000 lb. and the achievement of a thrust of 3,010 lb. Perhaps the satisfactory results which they had achieved with the straight-through combustion system was another example of the way in which they had fulfilled their predictions.

Mr. J. A. C. Manson (*Fellow*): Had Mr. Moult any information that he could give in regard to maintenance and production costs on turbine engines?

The statement had been made the previous day at the conference that maintenance experience showed that the amount of time involved in the maintenance of a turbine engine was something like one-fifth that needed for a piston engine.

Was there any indication of the trend of manufacturing costs?

Mr. Moult: A simple jet engine was fairly straightforward to maintain, but, as in most matters, they could pay their money and take their choice. They could rate an engine high and have a short life at a spectacular output, or they could have a more moderate rating and a longer overhaul period. He had run an individual engine for five to six hundred hours and there was nothing in it to indicate that it would not have gone on for twice that time. If they overstepped the limit in working temperature, the turbine blades, which were in the region of creep, would stretch. For military purposes, it might be necessary to run close to the wind and a high rate of replacement of critical items might be faced. The economics of civil operation would not permit this.

He agreed that maintenance costs for ordinary operation were probably considerably down on a normal piston engine and equally so, he thought, with regard to the cost of manufacture. If they considered the propeller and the radiator and all the accessories of the piston engine, the saving in cost was appreciable.

Mr. Manson: Was there a relation between the amount of power or the efficiency and performance that one could squeeze out of an engine and the specific fuel consumption? If they had an engine low-rated, not stressed to the limit of its power, did that mean that in order to get reliability they might have to put in a higher fuel consumption?

Mr. Moult: He did not agree. If they deliberately set out to design an engine for long life and did not object to its size or weight, then they could obtain a low specific fuel consumption, in fact a better one than for a highly-rated engine where everything was close to the limit.

Specific consumption was usually lowest just below maximum r.p.m. and increased rapidly at lower rotational speeds. For special purposes some adjustments were possible and it must not be inferred that a robust engine intended for long life was necessarily uneconomic.

The Chairman: He had been particularly pleased that Major Halford had spoken; it was most appropriate and his remarks were much to the point. He thought that all of them in the gas turbine world were in complete agreement as to what was wanted in the way of testing apparatus and all were doing their best to get it. They all realised the difficulties they were up against, difficulties, roughly speaking, which this country was up against. There were so many things vital to the national well-being — houses, power stations, and so on—that some of the things which gas turbine engineers demanded for their progress were forced a little into the background.

The Munich plant was an altitude plant which could test complete engines. Major Halford also spoke of component testing. He thought it true that there was no apparatus available in this country at the moment which was big enough to test separately the components of the latest aero-engines. They had two or three relatively small plants, nothing bigger than 6,000 h.p., and they must largely make do with them. But he would like everyone to know that all concerned with the business of component testing were doing all they possibly could to provide the apparatus as quickly as possible for that vital work to which Major Halford had drawn attention.

With regard to the spoiler, there was apparently a demand for producing drag on those very clean aeroplanes driven by turbine engines. There were people trying to produce it by an aerodynamic brake; the spoiler was in a different category. It spoiled about the same amount of thrust whatever the speed of the aircraft, whereas the braking effect of the aerodynamic brake diminished with the speed. The thrust spoiler was at the back end of the aeroplane, but he did not think it was very heavy. The thrust

spoiler installed for flight tests at the National Gas Turbine Establishment involved an additional weight of approximately 60 lb. in the region of the jet nozzle and approximately 40 lb. in the region of the c.g. of the aeroplane.

Mr. D. Anderson (*Student*) *contributed*: Mr. Moult had referred to improved materials for turbine discs and blades and had stressed the importance of cooling the disc on both sides. From this it would appear that the tendency in this country was to find improved materials for turbine blades to enable higher temperatures to be used. In Germany it seemed that a considerable measure of success had been achieved by use of turbine blade cooling in various forms and also by the use of ceramic materials.

Would Mr. Moult give his views on the question of using either blade cooling or ceramic blades as a means of permitting higher rating on jet engines in general and whether either of these methods could be applied to the Goblin engine; and if so, would the higher working temperature and consequently higher thrust be worth the extra cost?

Mr. Moult: As far as the Goblin was concerned they were interested both in improved materials and in the possibility of cooling the turbine wheel. Improved cooling had enabled a ferritic type of disc to be used at high gas temperatures with the many advantages set out in the paper.

Because of the shortage of alloys, the Germans had developed hollow blades in materials inferior to those used in this country. In taking this step they had compromised their blade sections and there was no doubt that their turbine efficiencies were inferior to British ones. How far it was possible to obtain the best of three worlds by combining cooled blades with the best materials and optimum aerodynamic shape was yet to be demonstrated.

It did not appear that the development of ceramic materials had yet reached a stage where they could be used with confidence at the temperatures and speeds of their existing turbine design.

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USEFUL LOAD RATIO WITH JET AND AIRSCREW PROPULSION OF AIRCRAFT

by

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Mr. Lundberg graduated from the Royal Technical University of Stockholm in 1931 *and has had wide experience as a test pilot and aircraft designer in Sweden. In* 1941 *he was responsible for the design of the Swedish Fighter J.22 which, because of a shortage in light alloy, was constructed in steel and wood according to a rather new principle of design. He has been in charge of the Structural Department of the Aeronautical Research Institute of Sweden since* 1944.

SUMMARY.

In a search for a rational basis for a transport-economical comparison of jet and airscrew propulsion of aircraft, a method has been developed which is generally applicable for evaluating any kind of propulsion of aircraft, as well as the efficiency of any principle or type of aeroplane design. The method is based on the assumption that the ratio between the useful load and the gross weight (or empty weight)—when related to the speed—is representative for the overall efficiency of the aircraft, including the power plant, from a transport point of view. General equations have been deduced for this useful load ratio as functions of, in addition to the speed and altitude, all major design parameters, as wing loading, power loading (or thrust loading for jet aeroplanes), specific engine weight, specific fuel consumption, parasite drag coefficient, effective aspect ratio, and two structural weight coefficients. This has been possible by the deduction of a formula for the gross weight, which appears to be usable even for general analysis of other aircraft performances, whenever the useful load has to be considered.

The method presented has been applied in this paper particularly for a comparison between jet-propelled aeroplanes and piston engine-airscrew aeroplanes. This has revealed that pure jet propulsion seems to be superior to the conventional system at speeds as low as 200 to 300 m.p.h., depending upon the duration in hours of flight and the detailed assumptions made.

Lack of accurate data for the gas turbine-airscrew combination has prevented the writer from making a closer investigation of this system, but a preliminary study of the same kind seems to indicate that the turbine-airscrew aeroplane—although for most purposes definitely superior to the piston engine aeroplane—is inferior to the pure jet aeroplane for durations up to about two hours of flight. If, however, all the mechanical complications involved in retaining the airscrew are taken into consideration, it appears doubtful whether the turbine-airscrew system will be any more than an intermediate step in aeronautical development. At the best, it might remain only for extremely long ranges, or transport of cargo at comparatively low speeds.

The conclusions drawn are based on the present stage of development of jet engines, but naturally it will take at least some three to six years before the jet aeroplanes contemplated are built and put into service.

This article is a summary of an investigation made in 1944 on behalf of the Royal Swedish Air Force following the news of Air Commodore Whittle's successful pioneer work on jet propulsion. The original purpose of this investigation was to find out to what extent jet propulsion would be likely to replace piston-engine airscrew propulsion in the future.

USEFUL LOAD RATIO FOR JET AND PISTON TYPES

INTRODUCTION.

In the development of aircraft, a number of figures of merit have been proposed for comparing aircraft of different types. The specific purpose of these figures of merit is mainly to form a basis for statistical comparison, from one point of view or another, of existing aircraft with known performances. As a rule, they are less suitable for preliminary design work or for predicting attainable performances of non-existent aircraft which might be designed according to different principles or equipped with various types of propulsive means.

Typical of one group of figures of merit which have been used is the ratio between propeller efficiency and the drag coefficient (η/C_D) when studying maximum speed performance. This number can be expressed as a simple function of certain essential design parameters, engine power, wing area and air density, which is an appreciable advantage, but it does not include the weight of the aircraft and consequently still less the payload or that part of the gross weight, which is of specific value for the user of the aeroplane. The useful load of an aircraft is of such fundamental importance that any figure of merit that does not specifically consider this part of the total weight has a doubtful value even for statistical comparisons.

There is, however, another group of figures of merit, which does take the useful load or the payload into account. The Mentzer-Nourse equation for the transportation cost is one of the best known and is no doubt excellent for statistical or economical comparisons for given transport aeroplanes. In such figures or equations, however, some of the most important design parameters of the aircraft are lacking — the parasite drag coefficient, the aspect ratio, the engine weight, etc.—these equations being concerned only with the results already attained with the aeroplane, in the first place payload, block speed and fuel consumption. Obviously such transport cost equations cannot be used either for preliminary design work or for answering the general question as to which combination of design features should be present in order to attain the desired results regarding transport performance of a contemplated new design of an aircraft.

The purpose of this paper is to present a method for calculating or predicting aircraft performance with particular attention to the useful load or payload, as well as the speed of the aeroplane, whereby all the major design parameters—such as drag, aspect ratio, wing loading, specific engine weight and fuel consumption, structural weight factors, etc., in all around twelve variables—are taken into consideration. This calls for a comparatively simple assumption as to the definition of a proper figure of merit, giving an overall picture of the quality of an aircraft. The author has come to the conclusion that the ratio between the specifically defined "total useful load" or the net payload and the all-up weight when plotted on speed, is a very important factor, which represents better than any other simple factor the aeroplane's —including the power plant's — transport economy or military transport value. Hence, general equations have been deduced for this useful load ratio as a function of speed and all the design parameters indicated above, for piston-engine airscrew propulsion as well as for pure jet propulsion.

For more detailed studies of aircraft performance, it is recommended to make use of the ratio between the net payload and the empty weight of the aeroplane, as this figure is still more representative. The equations for this figure, however, are somewhat more complicated, so the simpler ratio of total useful load to gross weight is recommended for most purposes.

Although this paper deals especially with the pure jet propulsion and the piston engine-airscrew types, it might be pointed out that the method presented of analysing or predicting the aircraft's qualities is not limited to these two methods of propulsion

or to conventional types of aircraft. The method is just as applicable for studying the inherent value of any other principle of propulsion or design of aircraft, such as the gas turbine-airscrew combination, rocket propulsion, the flying wing type, and so on. In these days, when we are just about to enter a new era of aviation in which almost anything seems possible, it might be worth while to devote some time and thought to theoretical studies of this general nature before starting the actual—and as a rule very expensive—design and construction of the more or less radical or fantastic new types of aircraft design which are to be expected.

OVERALL ENGINE EFFICIENCY.

As this study was begun primarily by a desire to compare the inherent possibilities of jet and piston engine-airscrew propulsion, something might be said about the propulsive efficiency as a means for comparison as well as about the difference in principle between these two engine systems from an aeronautical point of view.

The strongest argument against jet propulsion of aircraft has usually been the high fuel consumption, or the low efficiency of jet engines, in comparison with ordinary reciprocating engines. At 300 m.p.h., for instance, a jet motor has at present an overall propulsive efficiency of only about 10 or 11 per cent., while a good aero-engine of normal type has an efficiency of 25 per cent. or more, including propeller efficiency. Overall propulsive engine efficiency is here defined as the product of tractive or propulsive force and flying speed divided by the fuel energy consumption per unit of time.

$$\eta_e = C\left(\frac{TV}{F}\right) \quad . \quad . \quad (1)$$

where

T = thrust (lb.).
V = airspeed (m.p.h.).
F = fuel consumption (lb. per hour).
C = a function relating fuel weight to fuel energy, for a given calorific value of the fuel, making the right side dimensionless.

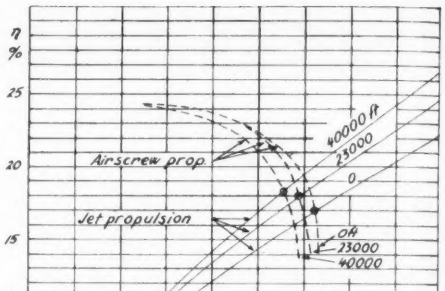

Fig. 1.
Total propulsive engine efficiency (including airscrew efficiency).

Overall efficiency of the jet increases with flying speed but 25 per cent. is not reached until a speed of 900 to 1,000 m.p.h. has been attained, as is shown by the example in Fig. 1. Parity with airscrew propulsion is attained earlier, at about 600 m.p.h. (or even earlier if the orthodox engine is not supercharged to the altitude in question), depending on the fact that the propeller efficiency falls off catastrophically due to bladetip losses at about 500 m.p.h. and over.

If the engine overall efficiency be compared in the two cases, the conclusion must be that jet propulsion is much inferior to propeller propulsion except for extreme high-speed aircraft, such as fighters. Engine overall efficiency is not, however, a sound basis for judging the aeronautical merits of the prime movers. This efficiency might be of value in comparing different makes of engines of the same principle, for example the piston type, but is actually misleading for a comparison of such widely different propulsive methods as jet and airscrew power.

THE DIFFERENCE IN PRINCIPLE BETWEEN JET AND AIRSCREW PROPULSION.

Between the two systems there is an important difference in principle. With jet power the propulsive force is practically constant with varying flying speed, while with a conventional motor-propeller combination, it is the horse-power which is approximately independent of speed, at least in the hitherto normal speed range. The difference can also be expressed by stating that for jet propulsion the horse-power increases in proportion to the speed, while with the airscrew the thrust of the propeller becomes less for increasing speed.

This difference in principle has been pointed out by several authors and is well known to all designers of jet aeroplanes but it is repeated here as being of particular importance for this study. Fig. 2 shows the variation of power and thrust with speed for a jet motor and for an engine-propeller installation, which give the same power and thrust at a certain speed—in this case 310 m.p.h.

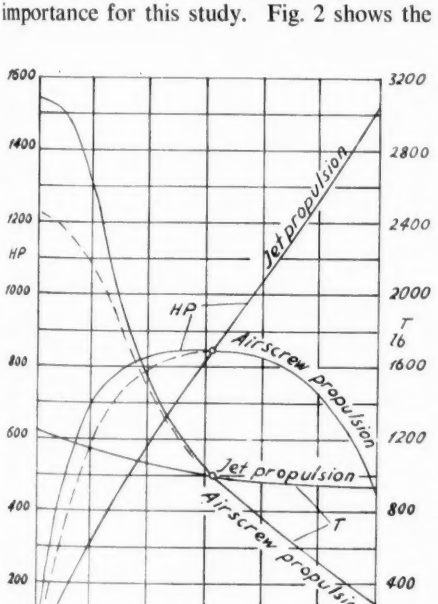

Fig. 2.
Typical variation of power and thrust with speed for jet and airscrew propulsion.

This fundamental difference makes it unsuitable to compare the two methods of propulsion either on the basis of power or thrust. Such comparisons should be made for a certain given speed if they are not to be misleading. Even so, it is easy to lose sight of the fact that jet propulsion has an important advantage in that the thrust does not decrease with increasing speed, whereas the designer of an airscrew aeroplane always has to face the fact that the cleaner he makes his aircraft, the less thrust can he get out of a given power plant.

Thrust is the proper basis for all aerodynamic calculations for jet propulsion, while horse-power is the natural basis of calculation for airscrew propulsion. In each case the basis for calculations should be that quantity which remains approximately constant at all speeds. This is technically correct, but it makes comparisons between the two systems difficult.

TRANSPORT EFFICIENCY ON A FUEL CONSUMPTION BASIS.

In the search for a rational basis of comparison of these two or any other methods of propulsion, we must free ourselves from the usual ways of thinking in terms of the characteristics of the engine plant, such as propulsive efficiency, thrust or horse-power. Instead, the chief object of the whole aircraft has to be considered, and this is always to be an instrument of *transport*. All aircraft, both civil and military, are intended for the transport at some suitable speed of a certain "useful" load, consisting of passengers or freight, or for military aircraft, bombs, weapons and ammunition. This goal—transport—must be the chief object to bear in mind when comparing different methods of propulsion as well as when comparing

different types or principles of aircraft design. For this reason we must take into account all factors which have a bearing on the aircraft's transport performance.

The useful load which can be carried at a certain speed must be given in relation to one or several other variables so that a figure of merit is defined, preferably as a dimensionless coefficient or at least, in principle, independent of the aircraft's and engine's absolute size. If the fuel consumption is taken as a primary factor, the "transport efficiency" can be defined as follows:

$$\eta_T = \frac{W_u S}{W_f} \times C = \frac{W_u V}{F} \times C \quad . \qquad (2)$$

where

W_u = useful load (lb.).
S = distance flown (miles).
W_f = fuel consumed (lb.).

This figure of merit—in which the thrust in equation (1) is replaced by the useful load—gives the transport capacity in lb. miles (or ton-miles) divided by the corresponding fuel-energy consumption. Strictly speaking, transport efficiency is not a real efficiency coefficient, as the direction of the force (weight) W_u is perpendicular to the direction of the motion S. This has no practical significance, however.

The transport efficiency according to the above definition would, from the aeronautical viewpoint, be a completely satisfactory basis for comparing different means of propulsion and for similar general investigations if fuel consumption were the only important, or at least the most important, economical factor to which the transport capacity should be related. Such is not the case, because the cost of the fuel does not dominate the total cost of transport. For commercial flying, about 15 to 20 per cent. of the operating cost corresponds to fuel costs and for military aviation it is only in the case of fuel shortage that fuel consumption has primary importance.

Jet engines use considerably cheaper fuel than the high-octane fuel used for modern aero-engines of the piston type. From the point of view of fuel economy it would be correct to put the price of the fuel in dollar/lb. in the denominator of equation (2), which would radically alter the fuel-economic transport efficiency in favour of jet propulsion.

Although transport efficiency as defined above (after correction for the price of the fuel) should thus replace the purely motor-technical overall efficiency, for all comparisons between different motors based on fuel economy, it is not a fully satisfactory basis for judging the total transport economy as explained above. It has been mentioned here merely as an intermediate step in this investigation and because it is always of at least theoretical interest to study the relationship between transport work and the corresponding energy consumption. To set up a "transport economy factor" which took care of all the many, and partly obscure, factors which influence the total costs would be difficult, at least if one wishes to attain a simple formula valid for both military and civil flying, and expressible as a function of the various design parameters. An approximation will have to suffice, where simplicity takes the place of detailed thoroughness.

THE USEFUL LOAD RATIO.

The writer has come to the conclusion that the ratio between the useful load and the all-up weight is a very important factor, which determines, better than any other simple figure of merit, the aeroplane's—including the power plant's—transport economy or military transport value. This figure, which in the following is called the "useful load ratio" is thus

$$\eta_W = \frac{W_u}{W} \quad . \quad . \quad . \qquad (3)$$

where W is the take-off weight.

The underlying idea for the use of this ratio is that most direct costs in commercial flying, as in all civil flying, seem to be proportional to, or dependent on, the size of the aeroplane, *i.e.* the all-up weight. Such is the

case regarding depreciation, hangar rents, landing fees and repair costs. With military aircraft it is even more apparent that the ability to carry as big a load as possible in relation to the size of the aeroplane is of vital importance, in addition to the maximum speed.

An argument against the "transport efficiency" as well as the "useful load ratio" as a basis for comparison might be that these two quantities do not stress the great significance of speed. But the importance of speed varies so much for different types of aircraft that it seems inadvisable to include the speed (or some function of it) in the expression for the figure of merit. The speed should therefore be studied together with the two figures of merit above and the most suitable way seems to be to observe the variation of the figures of merit as a function of speed.

THE WEIGHT EQUATION.

Equations (2) and (3) for the figures of merit discussed are no more than definition formulæ which in the form presented are only usable for statistical comparisons of existing aircraft. For general studies of the value of different principles or kinds of aircraft or engine design, the figures of merit must be expressed as functions of not only the speed but also of all the more important aerodynamic, structural and engine parameters of the aircraft. For this purpose a relation must first be found between the useful load and the gross weight, *i.e.* a weight equation which, with reasonable accuracy and generality, shows the all-up weight as a function of fundamental design quantities of the aircraft.

Various authors have presented more or less empirical equations or design charts for estimating the weight of the different parts of an aircraft, such as the wing, fuselage, tail group, landing gear and power plant. As far as is known to the writer, a comprehensive and general equation for the whole gross weight has not hitherto been put forward, probably because the all-up weight is built up of so many widely different parts, each of which varies in a complex way with a number of design parameters—where economical or even purely human factors often influence the degree to which weight-saving measures can be taken. An equation for the gross weight built up by a summation of the detailed weight equations for all main parts of the aircraft would be far too complicated to serve any practical purpose, but an approximate weight formula would be both sufficient and valuable for general investigations and preliminary design purposes.

To this end the gross weight has been split up in the following parts:—

$$W = W_s + W_b + W_e + W_f + W_t + W_u \quad . \quad (4)$$

where

W_s = the weight of all parts whose weights are proportional or nearly proportional to the wing surface, *i.e.* wing with ailerons and flaps, stabiliser, fin, elevator and rudder.

W_b = the weight of all parts whose weights are proportional to the gross weight, *i.e.* the landing gear, the main part of the fuselage, and some details or parts of details whose weights are likely to grow in approximately direct proportion to the size of the aircraft.

W_e = the weight of the complete power plant installation, including that small part of the fuel and oil systems, the weight of which is more dependent on the size of the engine than on the total amount of fuel.

W_f = the weight of the total fuel and oil.

W_t = the weight of the fuel and oil tanks.

W_u = the "total useful load" which might be defined as

$$W_u = W_c + W_a + W_p \quad . \quad . \quad (5)$$

where

W_c = the weight of all items or parts of details or equipment which do not belong to W_a or W_p as defined below, and which do not vary either with

change of the wing surface, the gross weight, the size of the engines, or the fuel quantity. The pilot's seat, the control column, the rudder pedals and certain parts of the fuselage belong to W_c.

W_p = payload or net useful load, *i.e.* passengers, mail and cargo for civil aircraft, and bombs, weapons, ammunition, etc., for military aircraft.

W_a = the weight of all accessories and equipment which are either necessary for carrying the payload or are proportional more to the payload (for instance the number of passengers) than to the size of the aircraft. Passenger chairs, part of air-conditioning system, etc., for civil aircraft, and bomb-racks, etc., for military aeroplanes, are examples of items belonging to W_a.

According to the definitions above, some of the main parts of the gross weight can be expressed as functions of vital design parameters, thus

$$W_s = (W_s/S)S = \frac{W_s/S}{W/S} W = w_s W \qquad (6)$$

and

$$W_b = w_b W \qquad (7)$$

where

w_s and w_b are the specific wing and fuselage weights.

For piston engine-airscrew aeroplanes

$$W_e = w_e P_o \qquad (8)$$

and

$$W_f = db_p tnP_o \qquad (9)$$

where

P_o = M.E.T.O.-horsepower (or any other basic horsepower value).

w_e = specific engine weight, lb./h.p.

d = the percentage of nP_o used in the case considered.

t = maximum hours of flight (corresponding to total range).

b_p = specific fuel consumption, lb./h.p. hr.

n = ratio between full power at any height and full power at sea level.

For jet aeroplanes the corresponding relationships are:

$$W_e = w_e T_o \qquad (8a)$$

and

$$W_f = db_j tnT_o \qquad (9a)$$

where

T_o = maximum thrust at sea level and zero airspeed (or any other suitable basic thrust value).

w_e = specific engine weight, lb. per lb. thrust.

b_j = specific fuel consumption, lb. per lb. thrust per hour.

Further the tank weight, W_t, can be written according to the definition

$$W_t = kW_f - W_f \qquad (10)$$

whereby

$$W_t + W_f = kW_f \qquad (11)$$

represents the weight dependent upon fuel consumption and flying time.

Equation (4) can now be written for airscrew aeroplanes:

$$W = (w_b + w_s)W + w_e P_o + kdb_p tnP_o + W_u \qquad (12)$$

and for jet aeroplanes:

$$W = (w_b + w_s)W + w_e T_o + kdb_j tnT_o + W_u \qquad (12a)$$

whence

$$W = C_w(w_e P_o + kdb_p tnP_o + W_u) \qquad (13)$$

and

$$W = C_w(w_e T_o + kdb_j tnT_o + W_u) \qquad (13a)$$

where in both cases

$$C_w = \frac{1}{(1 - w_b - w_s)} \qquad (14)$$

Although it is apparent that equation (13) is approximate and cannot possibly replace detailed weight analysis for parts of the aircraft, it does show the fundamental relationship between gross weight, engine size and characteristics, flying time and total useful load.

The writer has found, by using this formula for analysis of a considerable number of weight breakdowns for different types of civil and military aircraft, that the approximations involved in equation (13) are far less than could be anticipated from the complexity and number of factors determining the weight of

the aircraft. Naturally the structural weight coefficient, C_w, varies somewhat with the type and to a lesser extent with the size of the aircraft, and the tank-coefficient, k, varies with the type of tank construction, but by studying these variations for known aircraft a good basis is formed for predicting the gross weight for contemplated designs.

In this connection the part W_c of the total useful load has a certain regulating function in order to give the other weight-coefficients more constant values independent of the size of the aircraft. For example, the weight of the control systems does not vary in direct proportion with either the gross weight or the wing surface. It is then expedient to include in W_c a proper part of the weight of the control systems so that the remaining part would vary in approximately direct proportion with the size of the aircraft if this were changed during the preliminary design. It might also be emphasised that it is not possible to set up exact and consistent definitions of the three portions W_c, W_a and W_p of the total useful load W_u. Such definitions must always be subject to individual conceptions regarding the purpose of, or necessity for, the various equipment and other items included in W_u. From a theoretical point of view, the "total useful load," W_u, should be defined as that part of the aeroplane's weight which is independent of gross weight, wing area, engine weight or quantity of fuel. How this total useful load is utilised by the user of the aeroplane, *i.e.* to what extent it is used for real payload or, for example, navigational equipment, or armour plating, etc., is immaterial to the designer. For commercial aeroplanes the main part of W_u consists of payload, as a rule between 50 and 75 per cent.

It would be beyond the scope of this paper to discuss this weight equation too much in detail, but a few words might be said about the order of size of the various coefficients. In the first place **the piston engine-airscrew aeroplane** is considered.

The wing weight coefficient, w_s, can be written as is easily found

$$w_s = \frac{w_{sw}}{W/S}\left(1 + \frac{w_{st}}{w_{sw}}\frac{S_t}{S}\right) = \frac{w_{sm}}{W/S}. \quad (15)$$

where

w_{sw} = the specific wing weight including flaps and aileron, lb./sq. ft.

w_{st} = the specific tail surface weight, lb./sq. ft.

w_{sm} = the "overall" specific wing weight, lb. per sq. ft. wing area.

S_t = the total area of the tail surfaces.

S = wing area.

The specific wing weight, w_{sw} is highly dependent upon a number of factors such as load factor, wing loading, aspect ratio, planform, percentage wing section thickness, etc., but for modern, cantilever monoplanes it lies between the limits 3 and 5 lb./sq. ft. The specific tail surface weight w_{st}, is as a rule around 1.5 and 3 lb./sq. ft. With these average values and 25-30 per cent. tail surface area the "overall" specific wing weight will fall within the approximate limits 3.5 and 6 lb./sq. ft. Apparently the lower values occur at comparably low wing loadings and the higher values at higher wing loadings. Consequently, the wing weight coefficient according to equation (15) does not vary too much with the wing loading. As a matter of fact it is lower with higher wing loading because the "overall" specific wing weight does not increase in direct proportion to the wing loading. If, for example, 3.5 lb./sq. ft. overall wing weight corresponds to a wing loading of 17.5 lb./sq. ft. w_s will be 0.20, and if 6 lb./sq. ft. is combined with a wing loading of 60 lb./sq. ft. w_s will become only 0.10. These limits are usually too wide and a closer investigation of weight breakdowns reveals that the wing weight coefficient as a rule lies between 0.13 and 0.18.

The "body" weight coefficient, w_b, includes the landing gear and the main part of the fuselage as well as that part of the control systems, hydraulic, electric, and pneumatic equipment, etc., which can be assumed to be directly proportional to the gross weight. Retractable landing gears as a rule weigh 6

to 8.5 per cent. of the gross weight and the other parts between 7 and 14 per cent. The whole w_b therefore falls between 0.13 and 0.22.

The weight factor, c_w, will accordingly fall between the approximate limits

$$c_w = \frac{1}{1 - 0.13 - 0.13} = 1.35$$

and

$$c_w = \frac{1}{1 - 0.18 - 0.22} = 1.67$$

Here the two lowest and highest w_s and w_b values have been combined respectively, which is not likely to be the case in actual aircraft. The studies of weight breakdowns for aircraft types of all classes of civil and military aeroplanes have shown that c_w is seldom lower than 1.4 and never higher than 1.6 for piston engine-airscrew aeroplanes of normal design.

The tank weight factor, k, for fuel and oil tanks is highly dependent upon the type of tank construction. With integral wing fuel tanks it might be as low as 1.03 whereas it might rise to 1.2 for self-sealing and partly armour-protected tanks for military aircraft. A good average value is $k = 1.1$.

The specific engine weight, w_e, represents the sum of the dry engine weight and the weight of the airscrew and all engine accessories and controls. The dry engine seldom weighs less than 1.3 to 1.5 lb./h.p. and the weight of the complete engine installation, w_e, usually falls between 2.0 and 2.4 lb./h.p.

The specific fuel consumption, b_p, varies as far as the petrol is concerned between 0.40 and 0.50 lb./h.p./hr. As b_p according to the definition of w_f, includes the quantity of oil, the average value of b_p is about 0.46 to 0.48 lb./h.p./hr. for modern engines.

For **jet aeroplanes** some changes in the value of these coefficients can be anticipated as follows:

The *wing weight coefficient,* w_s is highly dependent upon the aspect ratio, especially for high-speed aeroplanes with thin wing profiles. The writer has made a comparative study of the problem of the optimum aspect ratio for airscrew and jet aeroplanes and found that for climbing as well as for long-range performance the jet types should have considerably smaller aspect ratio than the corresponding airscrew types. This is because the thrust of the jet engine is constant with speed, instead of falling off with speed as with airscrew aeroplanes, which means that the jet aeroplane will fly at a smaller angle of attack (smaller lift coefficient) for best climbing and range performance than the airscrew aeroplane.*

At a smaller lift coefficient the induced drag is less and the aspect ratio has less importance, and consequently can be decreased. How much smaller the aspect ratio should be can only be determined by a detailed study of the reduction in wing weight that can be attained; furthermore it depends upon a number of other aerodynamical and structural considerations. For jet fighters the writer has found that the optimum aspect ratio should be around 4.5 instead of the present normal value of 6 for airscrew-driven modern fighters.

The reduction in the wing weight coefficient, w_s, that can be anticipated with the lower aspect ratio is dependent upon many factors such as profile thickness, plan form, load factor, etc., and ought to be the object of further studies. It might roughly be estimated to be 10-20 per cent.

The "body" weight coefficient, w_b, will also be considerably lower with jet aeroplanes, chiefly because as a rule the landing gear can be made much shorter and therefore lighter

*It has been shown that the best rate of climb for a jet aeroplane is attained at a forward speed which is always higher—as a rule considerably higher—than the best gliding speed. The best gliding speed in turn is around 31 per cent. higher than the flying speed for minimum sinking speed, at which flying speed the airscrew aeroplane has its best rate of climb if the power is constant. For long-range performance, the optimum speed for piston engine-airscrew aeroplanes is the best gliding speed, whereas for jet aeroplanes it can be shown to be 31 per cent. higher (more exact $4\sqrt{3}-1 = 0.313$).

when the propellers disappear. As an average, the weight of the landing gear for jet aeroplanes might be assumed to be around two-thirds to three-quarters of the gear weight for airscrew aeroplanes. From equation (14) it follows that an improvement in w_b, corresponding to a reduction in the gear weight from, for example, 8 to 6 per cent. of the gross weight, reduces the value of the weight factor C_w from, say, 1.55 to 1.5.

The tank weight factor, k, can be slightly improved for jet aircraft because the denser fuel usable for jet engines requires less tank space per lb. fuel weight, whereas the calorific value per lb. is practically the same for both types of fuel.

The specific engine weight, w_e, and the specific fuel consumption, b_j, are not comparable for the two engine systems, as has previously been pointed out. For the former, figures of 0.4-0.6 lb. per lb. thrust and for the latter 1.0-1.3 lb. per lb. thrust per hour have already been attained in service with jet engines. Further improvements are anticipated.

THE FIGURES OF MERIT AS FUNCTIONS OF SPEED AND DESIGN PARAMETERS.

Although the deduced weight equation (13) will be used particularly for presenting the general relationship between the useful load ratio and the design parameters of an aeroplane, it might be emphasised that the weight equation is usable whenever any kind of performance is to be studied as a function of the load carrying ability, *e.g.* for range, climb, take-off or landing performance, and so on. As an interesting example it might be worth while to show how the maximum speed of an aircraft can be expressed in terms of the useful load. The general speed equation can be written

$$V = 52.73\left[\frac{W/S}{W}\,dnP_o\frac{\eta}{C_D}\frac{\rho_o}{\rho}\right]^{1/3}. \qquad (16)$$

At maximum speed d and n can be assumed to be 1.0. (Full power, the engine supercharged to the height in question.) By inserting the weight formula (13) the maximum speed equation can be written

$$V = 52.73\left[\frac{\frac{W}{S}\left(\frac{\rho_o}{\rho}\right)\left(\frac{\eta}{C_D C_w}\right)}{w_e + kbt + W_u/P_o}\right]^{1/3} \qquad (17)$$

This equation gives a clear view of the relationship between the maximum speed, the total useful load and the most important design parameters. The equation is especially useful in studying the controversial inter-relationship between speed, wing loading and useful load for a given engine and at a preassumed duration, keeping all the coefficients for aerodynamic (C_d), structural (C_w, k) and engine (w_e, b_p) qualities unaltered. Another interesting application of equation (17) is for studying the speed increase attainable in practice with increase of engine power. It is apparent from equation (17) that the speed does not increase at all with increase of power, unless the ratio between useful load and power is decreased, *i.e.* the useful load grows more slowly than the power. This gives a theoretical background for the well-known fact that a twin-engined aeroplane is by no means certain to be faster than a single-engined aeroplane. Even with a lower value of W_u/P_o an increase in the number of engines can easily cause an increase in the drag coefficient, C_D, which might more than compensate for the decrease in W_u/P_o, and the aeroplane with the greater number of engines might in fact be slower.

The transport efficiency, η_T. Substituting the total useful load W_u between equation (2) and (13) gives *for airscrew aeroplanes.*

$$\eta_{T_p} = \frac{WVt}{C_w W_f} - \frac{w_{ep}P_o Vt}{W_f} - \frac{kdnb_p tP_o Vt}{W_f}$$

But the fuel weight is

$$W_f = b_p tP = b_p tdnP_o$$

whereby

$$\eta_{T_p} = \frac{W}{P}\frac{V}{b_p C_w} - \frac{w_{ep}}{d_n b_p}V - ktV \qquad (18)$$

In order to introduce the aerodynamic

design parameters also, equation (18) is combined with the fundamental speed equation (16) by eliminating the power loading W/P.

$$\eta_{Tp} = \frac{146600\eta\,(W/S)\,(\rho_o/\rho)}{C_w C_{Do} C_i b_p V^2} - \frac{w_{ep}}{dnb_p} V - ktV \tag{19}$$

where

$$C_i = 1 + \frac{[391\,(W/S)\,(\rho_o/\rho)]^2}{\eta C_D\, A_e V^4} \quad . \tag{20}$$

is obtained from elementary theory, A_e being the efficient aspect ratio and C_{Do} the parasite or constant drag coefficient, assuming parabolic relationship between the drag and lift coefficients.

For jet aeroplanes, with constant thrust, the general speed equation is written preferably.

$$V = 19.77 \sqrt{\frac{(W/S)\,(\rho_o/\rho)}{C_D}\,\frac{T}{W}} \quad . \tag{21}$$

The general expression for the transport efficiency is obtained analogically as in the airscrew case

$$\eta_T = \frac{W}{T}\,\frac{V}{b_j C_w} - \frac{w_{ej}}{dnb_j} V - ktV \tag{22}$$

Eliminating the "thrust loading" W/T between equations (21) and (22) gives

$$\eta_{Tj} = \frac{391\,(W/S)\,(\rho_o/\rho)}{C_w C_D C_i b_j V} - \frac{w_{ej}}{dnb_j} - ktV \tag{23}$$

By plotting curves for η_{Tp} and η_{Tj} as functions of V on the same chart—assuming appropriate values for all the design parameters involved—interesting comparisons can be made between the two methods of propulsion. The intersection of such curves for the same duration might be called "the equivalent speed," above which the jet aeroplanes are superior to the airscrew types. According to equation (23) these equivalent speeds are independent of the duration if the fuel tank factor is assumed to be the same.

Comparisons of this nature will be exemplified only for the useful load ratio, as this case gives a still better picture of the overall quality of aircraft, including the engines, as previously explained.

The total useful load ratio. From equation (13) follows directly a general expression for the total useful load ratio, thus *for airscrew aeroplanes*:

$$\eta_{wp} = \frac{W_u}{W} = \frac{1}{C_w} - w_{ep}\frac{P_o}{W} - kdnb_p t\,\frac{P_o}{W} \tag{24}$$

and for jet aeroplanes:

$$\eta_{wj} = \frac{1}{C_w} - w_{ej}\frac{T_o}{W} - kdnb_j t\,\frac{T_o}{W} \tag{25}$$

Eliminating the power loading and the thrust loading between these two equations and the speed equations (16) and (21) respectively gives

$$\eta_{wp} = \frac{1}{C_w} - \frac{C_{Do} C_i V^3}{146600\eta\,(W/S)\,(\rho_o/\rho)}\left[\frac{w_{ep}}{dn} + kb_p t\right] \quad . \quad . \quad . \quad . \quad . \quad . \tag{26}$$

and

$$\eta_{wj} = \frac{1}{C_w} - \frac{C_{Do} C_i V^2}{391\,(W/S)\,(\rho_o/\rho)}\left[\frac{w_{ej}}{dn} + kb_j t\right] \tag{27}$$

These equations are general and may be used for studying any type or principle of aeroplane design or any method of propulsion. Fig. 3, which will be discussed later on, shows examples of them. Equation (26) is particularly applicable for the constant power case and equation (27) for the constant thrust case, but either can be used for any other variation of thrust or power with speed, pro-

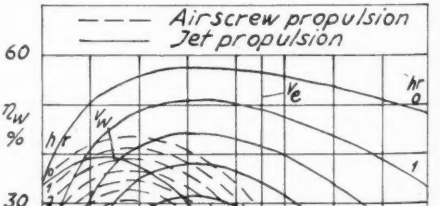

Fig. 3.

The useful load ratio versus speed with jet and airscrew propulsion. Altitude 23,000 ft., wing loading 41 lb./sq. ft.

vided that the corresponding variation with speed of the specific engine weight and the fuel consumption is taken into account. In most cases it is suitable to plot the useful load ratio as a function of speed for different values of either the duration—as in Fig. 3—or any of the design parameters involved, keeping the other quantities constant.

The useful load ratio as well as all the parameters, except speed and duration, are either dimensionless quantities (C_w, k, C_{D_0}, A_e, d, n, η, ρ_0/ρ) or ratios (W/S, w_e, b), whereby the inherent value of various design features — the flying wing principle for example—or propulsive means can be studied independent of the size of the aeroplane or the engines.

The fact that some of the variables, *e.g* the weight coefficient C_w, might vary slightly when very big changes of the size of aeroplanes are considered, has little practical significance. Apparently all the design parameters have to be chosen so that they apply as closely as possible to the type of aircraft considered, including a wide range of sizes.

The fact that a curve of the type described (Fig. 3) represents a certain quality of aircraft, regardless of size, makes it convenient also during the preliminary design stage for a contemplated new type to weigh the merits of load carrying capacity against the merits of speed. The design factor which determines the speed, *i.e.* determines a point on the curve, is apparently the power (or thrust) loading, and it follows from the deduction that the curves can be furnished with a scale representing the power loading. The gross weight of the aeroplane is then obtained by dividing the desired useful load in pounds with the useful load ratio, and the total engine power or engine thrust is obtained from the gross weight and the power (thrust) loading corresponding with the considered point of the curve.

This method is apparently useful at the first stage of preliminary design work or for similar general investigations, but it can also be used as a general performance calculation method, by which it is possible to calculate *what practical speeds can be attained by aeroplanes* which have to take a certain amount of useful load. This is a problem which cannot be solved by any of the conventional methods of calculating performance in which the aerodynamic qualities alone are compared with the available horsepower, disregarding any structural weight considerations. The question of whether or not any useful load—or even a pilot—can be included is not answered by such calculations. The meaning of the curves representing equations (26) or (27) (Fig. 3) may also be visualised by saying that only when a curve of this type—for sea level altitude and for very short duration—could be raised above the abscissa by an amount large enough to allow for the weight of a pilot, was flying made possible for the first time in the history of aviation.

Turning now to that particular application of the method with which this paper is mainly dealing, *i.e.* the comparison of jet and airscrew aeroplanes, it is obvious that in order to be accurate such comparisons should be confined, preferably, to particular classes of aeroplane, such as transports, small private aircraft, bombers, and so on. However, the writer has attempted to give a general, overall picture of the inherent possibilities of jet aeroplanes as a whole compared with the conventional piston engine - airscrew types, which necessitates choosing average values for the design parameters with due regard to military and civil aircraft as well as to the qualities of both air-cooled and liquid-cooled piston engines, and so on. The values chosen must be more or less arbitrary and subject to personal opinions. The equations (26) and (27), however, easily admit any other numerical figures to be used corresponding to any other individual opinion or any stage of aeronautical development. The numerical values of the quantities on which the curves shown in Fig. 3 are based, are:—

	Airscrew Type	*Jet Type*
H, ft.	23,000	23,000 (7,000 m.)
W/S, lb./sq. ft.	41	41 (200 kg./m.²)
C_w	1.55	1.50
k	1.1	1.1
C_{D_0}	0.017	0.0145
A_e (approx.)	5.35	5.35
w_e	2.2 lb./h.p.	0.5 lb./lb. thrust
b (incl. all oil)	0.42 lb./h.p./hr.	varies linearly from 0.83 at $V=0$ to 1.22 at $V=600$ m.p.h.
d	50%	63%
n	1.0	0.5
η	0.78	——

The assumed improvement of the weight coefficient, C_w, in the case of the jet has already been discussed. It corresponds only to the reduction in gear weight. No reduction in wing weight, corresponding to a lower optimum aspect ratio with the jet aeroplane, has been taken into consideration. The tank factor, k, is also conservatively kept the same for the jet as for the airscrew type. Regarding the parasite drag coefficient it might be emphasised that a jet-driven aeroplane should be much superior aerodynamically, compared with a propeller-driven aeroplane. The frontal area for a given power is much smaller; cooling drag disappears entirely; the slipstream drag behind the propeller disappears also, resulting in partial laminar air flow over those parts which are subjected to turbulent slipstream flow; and lastly, the jet engine can be built in much better from an aerodynamic viewpoint than a propeller power plant. In some cases the drag of the jet engine is non-existent, namely when the motor is entirely submerged in the wings or fuselage. These improvements have been estimated quantitatively, and amount to an average of at least 15 per cent., in many cases up to 40 per cent. The lower of these values has been used, which must be considered conservative.

The aspect ratio chosen might be a little low as an average value, but that does not noticeably affect the result. Most of the engine characteristics have already been discussed. The fuel consumption for the jet aeroplane has been assumed according to calculations furnished by a well-known Swedish turbine firm. It might seem a little low compared with most jet engines hitherto built, but it is not low in relation to what is to be expected in the near future—the Metropolitan Vickers axial flow jet engine is said to have attained already a consumption figure of 0.65 lb. per lb. thrust and hour. The fuel consumption for the airscrew aeroplane, 0.42 lb./h.p./hr., is low, considering that the oil consumption as well as the oil reserve is included.

The value of the relative power, d, for the jet aeroplane has been chosen so that the cruising speed would be the same percentage (about 80 per cent.) of the maximum speed as for the airscrew aeroplane, *i.e.* $d=0.5^{2/3}$. This assumption is admittedly rather arbitrary and to-day it seems likely that the jet engine will be able to run safely at a cruising thrust still closer to the maximum thrust, which is a considerable advantage for the jet engine compared with the piston engine. As the value of n indicates, the piston engine is assumed to be supercharged to the height in question ($n=1.0$), whereas the maximum thrust of the jet engine at 23,000 ft. has been assumed to be only half

maximum power at sea level and zero speed. (For Fig. 4 it has been assumed to be 0.8 at sea level and 0.3 at 40,000 ft.)

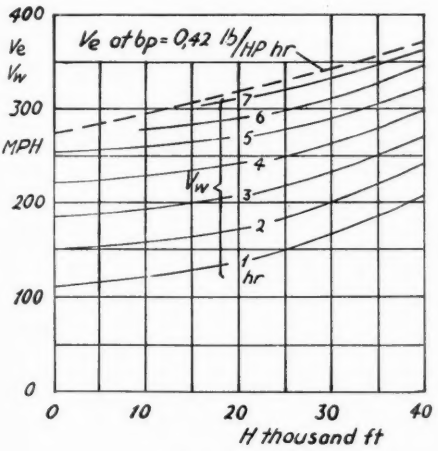

Fig. 4.
The equivalent speeds, V_w and V_e, for useful load ratio and "transport efficiency" respectively as functions of altitude. Wing loading 41 lb./sq. ft. The piston engine is assumed to be supercharged to the height considered.

As a whole it might safely be said that the figures used in this example are considerably more conservative for the jet aeroplane than for the airscrew aeroplane, especially if it is taken into account that the development foreseen for the jet engine will no doubt proceed at a faster rate than the improvements still to be expected with the piston engine.

In spite of the conservative assumptions made, the result of the comparison as shown in Fig. 3 is rather surprising. As is to be seen, the useful load ratio for jet types already equals that for airscrew types at speeds between 200 and 300 m.p.h. and above these speeds of equivalency the jet system becomes increasingly superior. This is quite a different picture of the possibilities of jet powered aircraft from that which was obtained from the overall engine efficiency, for which equality was first attained at about 600 m.p.h. and then only because of tip losses from the propeller. In Fig. 3 a curve has been drawn of "equivalent speed" for the same useful load ratios, *i.e.* a curve joining the points where the various flying time curves for jet and propeller cut each other. As was to be expected, the equivalent speed increases with the length of flight, depending on the higher fuel consumption with jet propulsion. This fact is also the cause of the greater spacing between the curves for jet propulsion. The fact that fuel consumption is not included in the definition of the useful load ratio does not mean evidently that the fuel consumption is ignored when using this figure of merit. It is taken care of to the right degree by the reduction in useful load which the fuel weight determines.

When judging Fig. 3 it must be kept in mind that each curve represents an indefinite number of aeroplanes having the qualities listed above but being of any size and corresponding to different values of power (thrust) loading. It is natural that some of the listed aircraft data in practice should be varied to a certain extent with speed. This applies especially to those qualities which determine the peaks of the curves, such as the best gliding speed. This, in turn for a given wing loading, altitude and parasite drag coefficient, is determined by the aspect ratio; consequently it might seem to be more adequate to vary the aspect ratio with speed, for example, in such a way that the useful load ratio would be the highest possible at every speed. If this is done the weight coefficient C_w should also be varied corresponding to the change in wing weight with the variation of the aspect ratio.

The author has made investigations of this kind and found that they lead to a flattening out of the curves with a less marked maximum, but that the result as far as a comparison between these two methods of propulsion is concerned will not be noticeably changed. It might also be pointed out that the aspect ratio for fighter aircraft, for example, is chosen mainly with regard to best

climbing performance and for other aircraft should be determined as a compromise between considerations regarding climbing as well as speed, range performances, and so on.

To sum up it might be said that the method presented and exemplified by Fig. 3—even if it might indicate somewhat impractical aircraft at speeds considerably below the speed for maximum useful load ratio—seems to be sufficiently reliable for comparative studies of the kind in question. The method is also considered to be sufficiently accurate for preliminary design surveys when a more limited speed range is investigated and the aspect ratio and other variables could be chosen with regard to a particular case.

Furthermore it should be emphasised that for aircraft corresponding to the very low "equivalent speeds" of Fig. 3 the piston-engined aeroplanes will no doubt have a considerably better take-off than the jet aeroplanes because of better thrust-weight ratio for the former. The take-off performance of the jet aeroplanes, however, can be sufficiently improved by rocket-assistance. Thus the take-off consideration hardly affects the conclusion that jet aeroplanes are superior to the piston-engined types at speeds above 200-300 m.p.h. In practice, however, these "equivalent speeds" are so low that probably they will never be used for jet aeroplanes and thus it seems to be merely an academical question as to whether the real equivalent speeds ought to be fixed at some 50 m.p.h. higher or lower value. As the equivalent speeds in any case are too low to be justified for jet aeroplanes the greatest value of comparisons according to the described method lies more in showing the difference in speed for a given useful load ratio ("horizontal comparison") or the difference in useful load ratio for a given speed ("vertical comparison") than in determining the curve of intersection.

The variation of equivalent speed with altitude and duration is shown by Fig. 4, which illustrates the same example as Fig. 3, except that the fuel consumption curve for the jet aeroplane is duly changed with different heights. As will be noted, the equivalent speeds increase with altitude. This is partly due to the assumption made when computing this diagram, that the piston engine is supercharged to the considered altitudes without taking into account any corresponding increase of the specific engine weight.

The payload ratio. As has been pointed out the total useful load, W_u, according to the definition includes not only the real useful load or payload but also the crew and all equipment necessary to carry the payload, as well as that part of the structural weight which does not primarily vary with either gross weight, wing surface, engine size or duration. For some purposes it might be worth while to study the net payload ratio instead of the total useful load ratio especially when transport aeroplanes are considered for which the payload can be sharply defined and is of primary importance. For these more accurate studies the gross weight should preferably be replaced by the empty weight, W_o, because it is actually the empty weight that is paid for and not the gross weight. This "payload ratio" can be written

$$\eta_p = \frac{W_p}{W_o} = \eta_w \frac{p}{W_o/W} \quad . \quad (28)$$

where

$$p = \frac{W_p}{W_u}$$

i.e. that part of W_u which is real payload.

The empty weight is

$$W_o = W - W_f - W_p \quad . \quad (29)$$

thus

$$W_o/W = 1 - W_f/W - p\eta_w$$

whereby

$$\eta_p = \frac{p\eta_w}{1 - W_f/W - p\eta_w} \quad . \quad (30)$$

The payload ratio can thus easily be calculated from the total useful load ratio if the value of p is known or estimated. Studies of weight breakdowns have shown that normally p is about 50 to 70 per cent.

It follows from equation (30) that the payload ratio increases with the higher value of the relative fuel weight, W_1/W; consequently this more accurate base for comparison will show a still greater superiority of the jet aeroplane to the airscrew aeroplane and correspondingly still lower equivalent speeds than is the case when the total useful load is the base for study.

THE POSSIBLE RANGE WITH JET AEROPLANES.

This study would be incomplete without mentioning a few words about the range attainable with jet aeroplanes as it is often felt that the use of jet power, because of the high fuel consumption, is confined necessarily to short range aeroplanes. A rough study of the range for any combination of the design parameters can be done easily by using charts of the type shown in Fig. 3, simply by multiplying the figures for duration with the corresponding speed. The result is presented preferably in the form used in Fig. 5, which illustrates the same example as Fig. 3. With 10 per cent total useful load ratio, for example, a range of about 2,000 miles can be attained with this combination of design parameters. Above the equivalent speeds the range is increasingly longer for jet than for airscrew aeroplanes.

With jet aeroplanes especially built for long range still higher range figures can be attained and there is another fact that favours the jet aeroplane considerably more than the airscrew aeroplane. This is that the gradual reduction of total weight as the fuel is consumed increases the range more, the more the take-off weight consists of fuel. For example, this increase is 10 per cent. if the initial fuel weight is one-third of the take-off weight, and as much as 20 per cent. for 55 per cent. fuel at take-off, a quantity of fuel which is not unthinkable for long-range jet aeroplanes.

After a close study of these factors, the author has come to the conclusion that at the present stage of jet engine development a

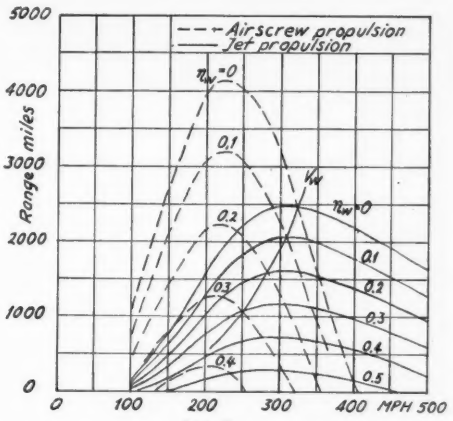

Fig. 5.

Range with jet and airscrew propulsion versus speed. Altitude 23,000 ft., wing loading 41 lb./sq. ft. Example corresponding to Fig. 3.

range of around 3,500 miles would be attainable and further, that a decrease of the fuel consumption (at sea level and zero speed) to around 0.65 lb. per lb. thrust and hour would make possible a range of about 5,000 miles or even more. This would make non-stop Atlantic flights between New York and Stockholm (4,000 miles) quite feasible with pure jet propulsion.

THE GAS TURBINE-AIRSCREW COMBINATION.

This combination is much superior to piston engine - airscrew propulsion and is considered by many as the right solution for transport aeroplanes, especially for long range purposes. As airscrew propulsion with the gas turbine also gives considerably better fuel economy than pure jet power, a comparison between these two means of propulsion must be done carefully. In this case the need for accuracy calls for use of the payload ratio instead of the total useful load ratio as the basis of comparison. As the author has not been able to obtain reliable figures for the specific weight and fuel consumption for the gas turbine-airscrew combination, no attempt will be made to compare numerically this means of propulsion with pure jet power.

A preliminary study has been made, however, based on estimated values for the qualities of the gas turbine, and it seems to indicate that as a rule pure jet power is superior as regards payload ratio for durations up to about two hours and that the gas turbine-propeller system becomes superior for longer durations. This refers to speeds where the propeller tip losses are not appreciable, *i.e.* below about 450 m.p.h. Above this approximate limit pure jet power is increasingly superior for all durations.

When studying this important problem proper consideration should be taken of all the mechanical complications involved by retaining the airscrew. The modern airscrew itself is a complicated piece of machinery with its blade adjusting device, de-icing equipment, and so on. Also, it necessitates a gear box with a very great reduction ratio and a high landing gear in order to get sufficient ground clearance. It should also be observed that a choice must be made between the tractor airscrew arrangement with its slipstream drag and turbulent boundary layer flow, or a pusher airscrew with the disadvantage that the exhaust gases must be led through long, drag-producing curved ducts to come outside the airscrew disc. On the other hand, the jet aeroplane will probably need rocket-assistance for the take-off in order to compare with the airscrew aeroplane in this respect.

Even when all the drawbacks with the gas turbine-propeller system are taken into account, by choosing appropriate values for the drag and weight coefficients and so on, the mechanical complications will probably result in an appreciably higher figure of cost per pound empty weight for the gas turbine-airscrew aeroplane than for the more simple pure jet. If this is the case, the denominator of the payload ratio ought to be multiplied with the empty weight cost in dollar per pound, which would markedly displace the equivalent speeds to still lower values and to longer durations than indicated above.

CONCLUSIONS.

Although the transport economy of aircraft is of a complex nature it is the author's opinion that the useful load to gross weight ratio, when related to speed, is a sufficiently accurate basis for preliminary design purposes as well as for general comparisons of different types of aircraft design or methods of propulsion. The method for analysing the useful load ratio has been shown by comparing jet and piston-engined airscrew aeroplanes. While such comparisons could also be made for particular classes of aircraft, the analysis in this paper is quite general and uses average quality figures for civil and military aircraft, the object being to get a broad view of the inherent possibilities of jet propulsion.

In spite of the fact that the quality figures chosen for the jet aeroplanes, according to the author's opinion, are conservative—especially in view of the rapid development expected—the comparison shows that jet propulsion is superior to piston engine-airscrew propulsion above such surprisingly low "equivalent speeds" as from 200 to 300 m.p.h. As such low speeds might be impractical for most types of jet aircraft the greatest interest of the comparison lies in studying the superiority of jet propulsion either in speed at a given useful load ratio, or in useful load ratio at a given speed. The example, Fig. 3, shows that in this case, an airscrew aeroplane designed, for example, for a duration of three hours, a useful load ratio of 20 per cent. and a cruising speed of 320 m.p.h. can be replaced by a jet aeroplane either having the same useful load ratio and 425 m.p.h. speed or the same speed and 35 per cent. useful load ratio.

Preliminary investigations which have been made seem to indicate further, that the jet aeroplane will be superior even to the gas turbine-airscrew type as regards the payload to empty weight ratio for durations—in the normal speed range—below about two hours, *i.e.* for the main part of all flying activity. If the complexity of the gas turbine- airscrew

aeroplane is properly taken into account, the jet aeroplane would appear to be economically superior up to still longer durations; probably up to about four hours. For still longer flight the inherent value of high speed, especially for passenger aeroplanes, is so great that it might be well worth while to step up to speeds in the compressibility field, where, probably, the airscrew aeroplane is out of the question. Hence, the turbine-airscrew combination will probably be an intermediate step only in development which, nevertheless, might remain for special purposes, such as extremely long ranges, or cargo transport at comparatively low speeds.

These conclusions are based on the present stage of development for jet engines and do not take into account the possibility of great improvements. On the other hand, it will take some three to six years at least before commercial jet aeroplanes can be built, thoroughly tested and put into service.

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STABILITY OF AN AIRCRAFT STRUCTURE IN A STRENGTH TEST FRAME

by

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1. INTRODUCTION.

1.1. The part played by major structural strength tests in aeroplane design is well known. Without such tests the standard of safety for aircraft would soon decline and excess weight, as an insurance against structural failure, would become a general rule. Considerable time and effort are expended therefore in the early stages of each new design of aeroplane to check by actual test whether its strength meets requirements. It is clearly reasonable to devote some little further time and effort to the study of methods and technique for strength testing in general.

The strength testing of an aeroplane is undoubtedly a complex scientific problem. No two tests are alike. The variety of aircraft types and the diversity of loading conditions require each test to be made the object of special study. Improvisation is almost always necessary if the best results are to be obtained. Design of testing apparatus has to be governed by these considerations in order to give the widest range of adaptability and to enable time to be saved wherever possible.

1.2. Test engineers and test frame designers bring to this work a vast amount of skill and traditional knowledge supported by engineering judgment. These qualities cannot be ignored in any study of the aircraft testing problem. They have made strength testing as much an art as a science. Without them no set of rules or guiding principles can be of any use.

Nevertheless, there are indications that more time could usefully be given to the study of underlying scientific principles. A most promising field is that concerned with the various adverse phenomena which have the general character of instability, and from this field there might well be selected the uncontrolled displacement of the test specimen.

1.3. Most aircraft engineers are familiar with the way in which an aircraft may move about inside a test frame during the process of load application. Such motion may be rotational or translational, although more frequently it is rotational. It may be to and fro or in one direction. In its severest forms it may prevent a test being completed, or at least invalidate the test results.

The phenomenon becomes more likely to occur as aircraft increase in size, when prevention becomes more difficult. It is also more likely to occur as the degree of mechanisation increases and manual control declines. On two counts, therefore, it is likely to present an increasingly difficult problem as time goes on.

1.4 In the following analytical study of uncontrolled displacement the conclusion is

reached that there is no direct way of preventing it. Uncontrolled displacement is liable to occur whenever there is more than one screw-jack or equivalent loading device. On average-sized aircraft there are usually several of these and the number increases as the aircraft become larger.

By the judicious use of constraints and linkages the order of potential instability can be reduced, but almost always there remains at least one degree of freedom usually rotational.

A proposal is made for an entirely different approach to the problem, by the introduction of an over-riding automatic control. A detecting device, which might conveniently be electrical, registers overall displacement and imposes increments of load at each loading station. These increments act in the sense required for restoration of the original position of the test specimen, and are distributed in a way which minimises the probable loading error at the individual stations.

1.5. Reasons are given to suppose that the stabilising system suggested is both practical and simple, and should not interfere with the normal loading process. It is thought, moreover, that some such system will become essential as mechanised loading develops and as the size of the larger aircraft increases.

There are also indications that stabilisation will enable fairly radical improvements to be made in testing technique, with the object of reducing the time taken. At present most of the time required for a strength test is expended on design and manufacture of mechanical linkages. With automatic stabilisation, and preferably with mechanised load application, it should be possible greatly to reduce the linkage system.

2. GENERAL TEST INSTABILITY.

2.1. There are several forms which instability of the loading system may take in a strength test. It is not practicable to discuss them all, but for methods of test reasonably in accord with present-day practice they may be reduced effectively to three, namely:—

(a) Ordinary instability.
(b) Unstable load distribution.
(c) Uncontrolled overall displacement of the specimen.

2.2. Ordinary instability is that met with in conventional mechanics. At any instant the loading system may be unstable irrespective of what stage has been reached in the loading process. Since the problems encountered are not peculiar to strength testing, detailed comment is unnecessary. There should be mentioned, however, the complication introduced by the flexibility of the test specimen. Another complication would be interaction with the load application system, were not this usually irreversible in modern practice.

2.3. Instability of load distribution is an entirely different phenomenon which arises in the course of detailed load adjustment. It is usual to reach the specified loading condition in successive incremental stages, the forces at any one stage being a fixed fraction of those specified. In proceeding from one increment of total load to the next, detail adjustment of individual loads has to be made. During this adjustment the laws of equilibrium cannot be circumvented and intentional alteration of one load may have undesirable effects on some of the others. The instability arises when the load system as a whole is so sensitive to imposed changes in individual loads that the required loading system can only be achieved or sustained with difficulty, or in extreme cases cannot be achieved or sustained at all.

2.4. The third form of instability, uncontrolled displacement of the test specimen, is liable to occur in all stages of the loading process and especially, in the passage from one intermediate loading case to the next. In general, the phenomenon can occur only when there are a number of independent load application devices. The motion at each loading station is the combined effect of deformation of the specimen and its overall

displacement. The displacement component may be indeterminate on a first assessment, being unrelated to the magnitude of the forces applied. In practice the overall displacement may occur as a direct divergence in one direction, rotational or translational, or as oscillation of increasing amplitude.

2.5. At this stage it is necessary to narrow the field of investigation by making allowance for modern procedure, or reasonable departures therefrom. The use of several independent loading jacks is assumed, as also is their complete irreversibility.* Given these conditions and the existing degree of flexibility of aircraft structures generally, it may be assumed that the test engineer and test frame designer can cope with any danger of ordinary instability and with any difficulties of load adjustment.

Uncontrolled displacement, on the other hand, can be difficult to avoid. It is manifest in some degree in almost all tests except the simplest. It may be shown, moreover, that modern trends of development increase the prospect of trouble from this cause. Uncontrolled displacement is therefore selected for detailed study as a modern problem. The other forms of instability remain in the background, but are still potential risks when special efforts are made to prevent uncontrolled displacement.

3. UNCONTROLLED DISPLACEMENT.

3.1. A comprehensive view of the whole problem of uncontrolled displacement may be obtained from the general two-dimensional case illustrated in Fig. 2, *conventionalised* in accordance with Fig. 1. In this test forces are applied by irreversible loading jacks through comparatively long rods or wires. At any instant the system is stable and the position of the specimen is fixed. In the process of loading, however, the specimen has three degrees of freedom and there is no direct control of its position. The corresponding problem in three dimensions is more complex, but does not introduce any new principles.

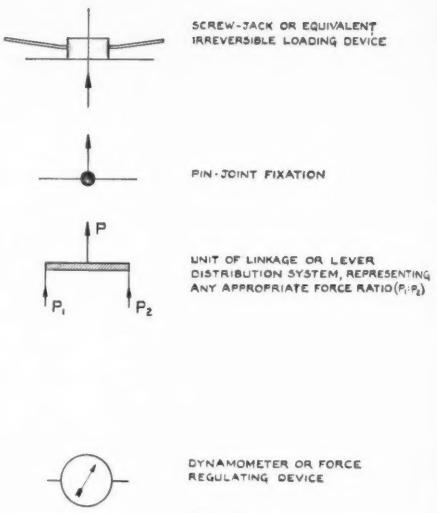
SCREW-JACK OR EQUIVALENT IRREVERSIBLE LOADING DEVICE
PIN-JOINT FIXATION
P
P1
P2
UNIT OF LINKAGE OR LEVER DISTRIBUTION SYSTEM, REPRESENTING ANY APPROPRIATE FORCE RATIO (P1:P2)
DYNAMOMETER OR FORCE REGULATING DEVICE

Fig. 1.
Diagrammatic conventions used in subsequent illustrations for items of testing equipment.

3.2. The functional aspects of uncontrolled displacement are best studied, in the first

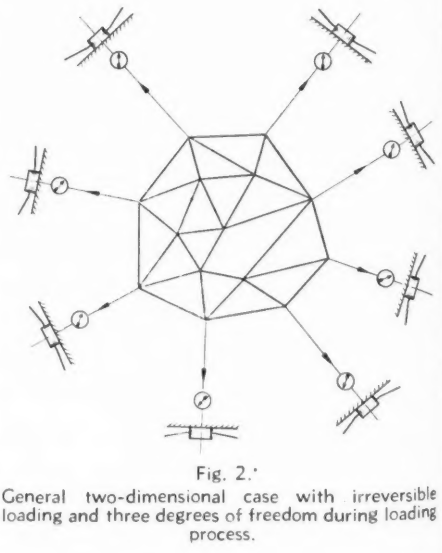

Fig. 2.*
General two-dimensional case with irreversible loading and three degrees of freedom during loading process.

*In practice there is sometimes a small amount of reversible travel within definite limits and heavily damped, which for the purpose of general discussion has been ignored.

instance, for a somewhat hypothetical test involving only one degree of freedom, but done under conditions representative of the more general case. Two opposed forces (Fig. 3) are applied to a test specimen by

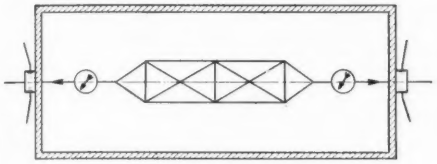

Fig. 3.
Tensile-test with two screw jacks and independent dynamometers.

means of separate irreversible loading jacks. Separate operators are assumed to control them, being guided by independent dynamometers. The worst conditions for uncontrolled displacement arise when the operators attempt to apply equal and prearranged increments, but otherwise act independently.

3.3. Under these rather hypothetical conditions there are two quite distinct phenomenon which may arise, both contributions to uncontrolled displacement. First, since no two mechanical devices are identical and since no two operators work in exactly the same way, one jack will wind in quicker than the other. Hence with each increment of load the test specimen will undergo overall displacement. Unless there be deliberate intervention by the operators the effect is likely to be cumulative and might prevent the test from being completed.

The second effect, in its extreme form, is more serious. If the operators act strictly according to instructions, the least discrepancy in the dynamometer readings will cause one jack to wind in more than the other and, in fact, one may wind in and the other pay out until the specimen has reached the limits of the testing machine.

3.4. In practice, these effects would be modified by deliberate intervention by the operators, who would perceive what was happening. It would not be possible to prevent a certain amount of motion to and fro during the test, but by accepting a slightly incorrect reading of load the operators would probably succeed in keeping the specimen within the limits of the apparatus.

On the other hand, a simple mechanised version of this loading system, directly replacing manual operators, would not be able to show such discrimination and would slavishly respond to readings of the respective load indicating devices. This illustrates in a simple way the increased risk of uncontrolled displacement with mechanised loading systems.

3.5. The same kind of phenomena occurs with a complex structure under a complex loading system, but the tendency for the test specimen to move during the loading process is greater and remedial action is more difficult. The adverse effects are exaggerated by the multiplicity of loading jacks and the increased number of degrees of freedom. The relationship between the travels at the loading jacks corresponding to rigid body displacement is much more complex and the travels corresponding to deformation vary considerably with position on the test specimen. Hence, greater reliance has to be placed on control through force measurement and less regard can be paid to displacements.

The essential factors contributing to uncontrolled displacement, however, remain substantially the same as for the simple tensile case, and may be generalised as follows:—

(a) Disproportionate rate of winding in of the loading jacks.
(b) Inaccuracies of the load measuring or load controlling devices.
(c) Manual intervention in an attempt to correct for the effects of these.

3.6. It is instructive to consider next how uncontrolled displacement could be prevented in the simple tensile test described above. In a normal tensile test, the phenomenon does not arise at all. There is only one loading jack and the absent one is replaced

by a simple anchorage. Direct extension of the analogy to more complex tests has to be qualified, but there are two possibilities. A number of anchorages or constraints may be introduced in numbers appropriate to the increased degrees of freedom. The alternative is to reduce the force system by mechanical linkages to two opposed forces, or to two or three such pairs mutually at right angles. Both these methods are discussed below.

4. THE USE OF CONSTRAINT.

4.1. At first sight, the introduction of constraints into the loading system would appear to be the simplest and most direct way of preventing uncontrolled displacement. The degree of fixation of the test specimen must, of course, be just sufficient to prevent displacement without introducing redundancy. As a general principle, it then follows that the reactions at the constraints will be determinate and consistent with the specified loading condition.

Direct fixation of the test specimen, however, can give rise to serious difficulties and the consequences may be more serious than the original trouble. The most straightforward course at this stage would be to consider the most general case, but in tackling this problem the greatest possible use has to be made of the peculiarities of a particular loading system. An aircraft is symmetrical and some of the most important loading conditions are symmetrical also. The main loading actions, if not all, moreover, are frequently parallel. In the following analytical treatment of the subject the general two-dimensional case is considered and followed by representative cases such as arise in strength tests of actual aircraft.

4.2. The starting place for the general two-dimensional case is the diagram shown in Fig. 2, where an intrinsically stable system of forces is applied by means of irreversible loading jacks. The simplest way of giving the necessary fixation without redundancy is to replace three of the loading jacks by pin-joint attachments to the test frame structure, as represented diagrammatically in Fig. 4. An alternative would be to have only two such anchorages, one being on the structure itself, but this involves no change in fundamental principle.

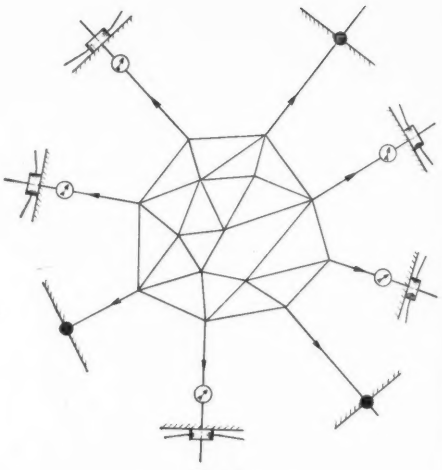

Fig. 4.
General two-dimensional loading case with sufficient constraint for complete fixation.

4.3. Now, although the constraint is not redundant there is clearly a danger of its being critical. The three reactions could conceivably pass through a single point, in which case an additional loading system might be introduced that is entirely independent of the main loading system.

In practice, the exact critical condition is unlikely to occur, but a condition sufficiently near to it might arise to make the loads imposed unrepresentative. The consequences, moreover, might be seriously aggravated by the legitimate deformation of the structure under the deliberately applied forces. In other words, the fixation system might tend to "pinch" the structure.

Further discussion has no purpose unless it can be assumed that the test engineer would avoid critical constraints. The risk is there, however, and efforts to avoid the critical condition may impose a serious handicap.

4.4. If the constraining system is both non-redundant and non-critical there is another disadvantage to the use of constraints for avoiding uncontrolled displacement. The three dead reactions are determined by the laws of equilibrium. For these reactions to be correct three conditions must be satisfied: —

(a) The specified loading case must be exact and, in particular, must exactly satisfy the laws of equilibrium.

(b) The geometry of the system must be precisely correct.

(c) The applied forces called for must be correctly reproduced.

In practice none of these conditions is satisfied and there is a danger of the errors accumulating at one or more of the reaction points. Thus, while errors comparable with those for the controlled loads would normally be acceptable for the dead reactions, they can actually be much greater.

The effect may be increased in the intermediate loading stages when the controlled loads are being adjusted. The dead reactions may then have to provide temporarily very heavy balancing loads.

Should the dead reactions replace comparatively small applied loads, at correspondingly weak parts of the structure, premature and unrealistic failure may occur locally. Even with a system of roughly equal loads there is a danger in discriminating between them and in making the few selected forces compensate for all the errors in the system. The use of constraints, in fact, is legitimate only when they are used to replace very heavy loads, so that the proportional error is negligible.

Examples of both satisfactory and unsatisfactory constraint, from the standpoint of errors, are found in the case illustrated in Fig. 5, which is closely representative of an actual test on a complete wing structure.

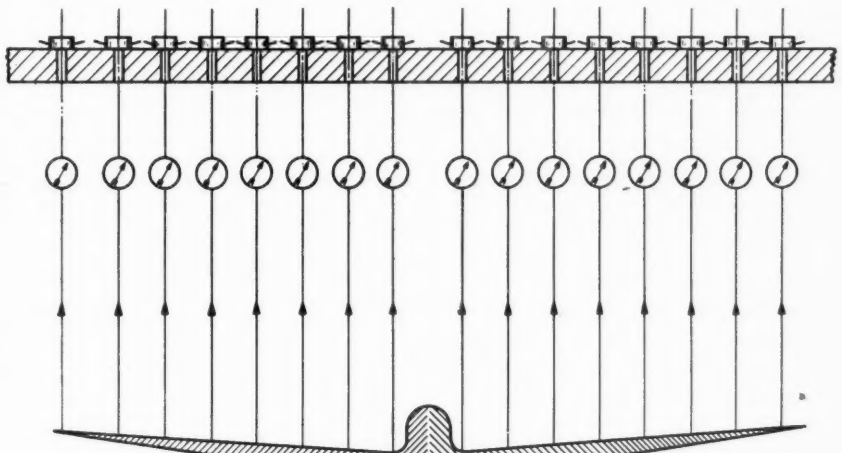

Fig. 5.
Example showing legitimate vertical constraint and the difficulties of rotational constraint.

Here the load on the fuselage balances the entire aerodynamic loading system and can be replaced by a constraint.

This constraint prevents only vertical displacements and the system is still free to rotate. The distributed aerodynamic lift on the wings is represented by a large number of small loads. To apply the principle of constraint, one of these has to be selected for being replaced by a dead reaction. It is clear that serious errors might be introduced by this process.

4.5. There is a third difficulty with the use of constraints which is not only serious in itself, but tends to prevent any attempts to overcome those difficulties associated with errors in the loading system. Deformation of the system under the applied loads is, in practice, considerable. Fixation of any one point, therefore, may give rise to forced overall displacement as serious as the uncontrolled displacement.

The effect is best seen in the use of constraint to prevent uncontrolled rotational displacement in the wing test of Fig. 5. Fixation of any point on one wing would cause the whole aircraft to rotate as loads were increased. This in itself would tend to invalidate the test by orientation of the direction of the applied forces relative to the test specimen.

In practice the adverse consequences of such constraints are increased by the effects of gravitational force, which has not so far been mentioned. The weight of the test specimen and of ancillary test gear are best compensated by an independent loading system, although a correction might be applied to the main loading system specified for the test. Either way, the compensation becomes completely inaccurate as the aircraft rotates and there may even be a danger of the whole system becoming unstable in the ordinary sense.

4.6. The general conclusion is reached, therefore, that the use of constraints to prevent uncontrolled displacement creates many difficulties and has only limited practical application. Care is necessary to ensure that the constraining system does not introduce a virtually independent loading system or restrict the normal deformation of the specimen under load. Given this care, there is still a danger of introducing unacceptable errors in the loading system.

5.1. The linkage method of preventing uncontrolled displacement gives a closer analogy to the simple tensile test than does the general use of constraints. In this method, when the applied forces are all parallel, they are reduced to two opposed forces by a system of levers. One of the forces is then applied by means of an irreversible loading jack and the other is the corresponding reaction from a suitable anchorage on the test frame. The complete system is represented diagrammatically in Fig. 6.

5.2. The linkage mechanism is similar to that in common use for reducing the number of screw jacks required for a large number of loading points on the specimen, but is

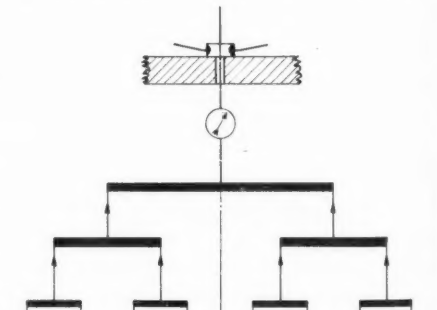

Fig. 6.
Linkage system carried to extreme in order to eliminate uncontrolled displacement.

carried to a higher degree of reduction. The method is especially appropriate to systems of parallel forces, which need not necessarily lie in a plane, although shown that way in Fig. 6. The method might be extended, moreover, to systems with forces acting in various directions by the use of two or three independent and mutually perpendicular systems. This kind of independent loading is frequently used to reproduce side forces on an aircraft.

5.3. In theory, this method of eliminating uncontrolled displacement is the ideal, and a complete solution to the problem. Unfortunately, there are three major practical difficulties which arise for tests on actual aircraft of any appreciable size, and these apply a serious limitation on the usefulness of the principle.

5.4. In the first place, as loading points on the airframe increase in number and as aircraft increase in size, the size and weight of the leverage system increases disproportionately. For an aircraft of quite small size the use of a complete linkage system reducing to one loading jack is quite impracticable. Even if the design and manufacture of the gear could be undertaken, its weight would render the test results seriously inaccurate.

5.5. In the second place, the design and manufacture of elaborate linkage systems absorbs time and effort which cannot be spared. The whole linkage system needs completely new design for each aircraft tested and radical revision for each different loading case. With the compromise arrangement at present in general use in this country, in which restricted numbers of linkages are used, the design and manufacture of these absorbs too much of the time required for a complete test. It would be unwise to call for linkage equipment taking still longer to design and manufacture.

5.6. Finally, there is a danger of ordinary instability from the unrestricted use of linkage systems. There are obvious dangers, for example, in suspending an aircraft from a single point as in Fig. 6. Unless great care is taken to design for ordinary stability the whole system may rotate. Moreover, caution is necessary in designing for ordinary stability, since excessive restoring forces introduce errors into the loading system.

5.7. Because of these three disadvantages the unrestricted use of linkage gear is not acceptable for tests on actual aircraft of any appreciable size. The method may be used on small aircraft, or small components, and it may be used in part to reduce the tendency towards uncontrolled displacement on larger aircraft. It does not provide, however, a complete solution to the problem of preventing uncontrolled displacement in tests on present-day aircraft types.

6. THE FINAL PROBLEM.

6.1. From the foregoing discussion of constraints and linkages it is clear that there still remains a problem in uncontrolled displacement, to which these do not provide a complete or an entirely acceptable solution. An example is the wing test shown diagrammatically in Fig. 7. Here a single constraint is used to give vertical anchorage and linkages are used to the greatest practical extent, but there is freedom to rotate during the loading process. There are other examples occurring in aircraft strength testing, but this one is typical.

6.2. It is appropriate to consider first how this problem has been treated in the past. A review of test procedure indicates that uncontrolled displacement has not always been apparent, or has not usually been regarded as serious. More especially does this conclusion apply to test frames incorporating man-operated loading winches.

There appear to be two reasons. The first is the existence of friction in the loading system. The second is manual intervention involving an unspecified and arbitrary interference with the loading system. In principle, both factors are forms of constraint of an indeterminate kind. Sometimes the errors

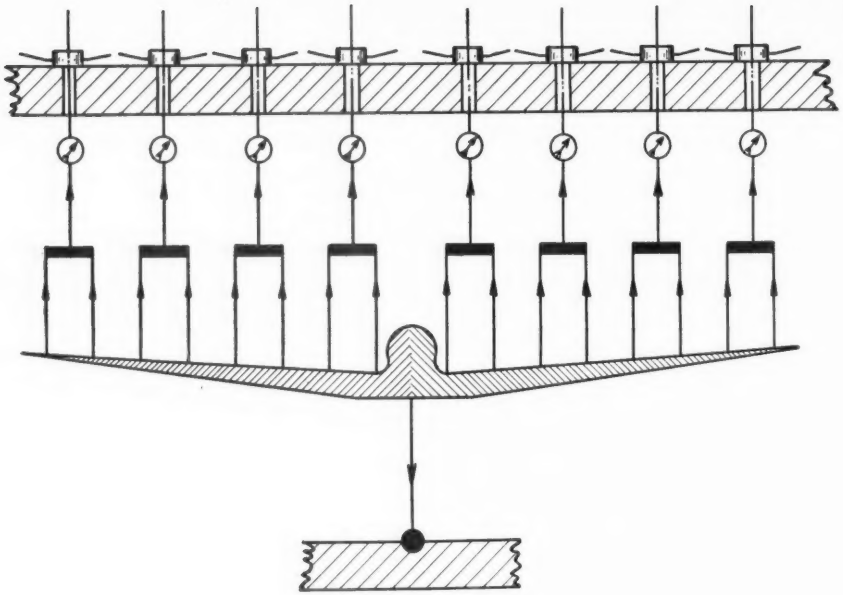

Fig. 7.
The final problem—restricted use of constraint and linkages permitting uncontrolled rotational displacement.

associated with constraint may have been well distributed. On the other hand, they may have been badly distributed, or even increased in absolute magnitude by what virtually amounts to a redundancy of constraint.

6.3. For the future, the prospects of these dubious methods of overcoming or disguising positional instability are poor. With mechanised load application there is little room for manual intervention and there is a natural tendency to eliminate friction so far as possible. In any case, reliance on these methods of stabilisation is unsound and is likely to be avoided as much as possible in the future.

The need for increased use of mechanised load application is strong. The man-power required for winch operation is already excessive. In addition, it is becoming necessary to test aircraft when loaded and unloaded several times, for which a quick mechanical process is essential.

The need for reducing the time expended on strength tests will also influence the methods used to overcome uncontrolled displacement. This is a further argument for mechanised load application, but not of first importance since, apart from repeated loading, the saving in time is probably small. The main effect concerns the design and manufacture of linkages, which absorb the major portion of total testing time. Reduction in the order and number of linkages thus becomes a primary objective, but as it incurs an increase in the number of independent loading jacks, it will tend to aggravate the tendency for uncontrolled displacement.

It follows therefore that, while there is already a problem which needs to be solved as a matter of principle, future developments are likely to make its solution an urgent necessity.

6.4. In seeking to prevent uncontrolled displacement when other methods have failed, or are only partially successful, there is one

field which still remains to be explored. This is the use of automatic control responding to displacement. A method is proposed for introducing additional stabilising forces to the extent required as the aircraft shows signs of overall motion away from its original position.

In the example requiring rotational stabilisation (Fig. 7) a detecting device is attached to the fuselage which transmits different signals as the aircraft rotates one way or the other. The precise details of this device are not important, although for the purpose of this discussion it is convenient to assume electrical operation, so that one of two circuits is closed when the aircraft rotates a predetermined small amount.

The appropriate signal imposes increments of load at all the loading jacks, in magnitude proportional to the force normally applied there and in direction, appropriate to restoration of the original position of the aircraft. In this way the required restoring forces are produced without accumulation of excessive error in any one loading station.

This automatic adjustment of load is not instantaneous. It merely alters the total load which each individual loading jack will endeavour to maintain. The stabilising load system is thus superimposed on the normal loading system and the entire process of primary load adjustment is done in the nomal way.

6.5. The method is put forward as a general principle, with scope for widely different interpretations in detail application. Nevertheless, it is instructive to consider broadly its use with a system having hydraulic load control, of a kind in more or less general use in this country.

In this system each loading jack is balanced against a small hydraulic ram and the leverage is so arranged that the pressures in all the rams need to be the same, a condition satisfied by direct interconnection of pipe lines. Increments of total load are accompanied by increase of the hydraulic pressure.

Under the proposed scheme for rotational stabilisation, the hydraulic systems for the two sides of the aircraft are kept separate. Their pressures are approximately the same, but one is slightly greater than the normal and the other slightly less, in accordance with the signals received from the position detector on the fuselage.*

6.6. There remains to be considered the behaviour of the stabilising system in the light of the fundamental causes of instability enumerated in the initial analysis (§2).

There is first the effect of errors in the individual load measuring devices and in the mechanism of response, which make it impossible to obtain true balance and which lead to drastic overall movement in the attempt to reach this unattainable balance. Clearly this tendency can be completely overcome, provided that the stabilising load increments are sufficiently great. In other words, exact balance ceases to be the objective of the system, but the degree of unbalance is under control.

The second effect is disproportionate winding of the loading jacks. The method proposed will not prevent displacement through this cause, but it will prevent its being cumulative. For each increment of total load the aircraft must ultimately settle down to its original position in the process of load adjustment. Displacements cannot be carried over therefore from one intermediate stage of total load to the next.

Finally, there is manual intervention, normally applied to prevent excessive displacement, but also modifying the general character of the instability, especially when made in accordance with a definite plan. With the proposed over-riding device, manual

*In a paper "The de Havilland Wing Test Rig" (Journal R.Ae.S., April 1946), W. Hampton suggests differential pressure as a means for restoring the rotational position of the specimen by deliberate manual intervention.

interference should be entirely unnecessary. Thus, even with hand-operated winches, the operators will need to pay attention only to load indication without regard to displacements. With mechanised load application, on the other hand, loading and stabilising becomes a single automatic process.

6.7. The case is thus presented for uncontrolled displacement being completely prevented by an over-riding and automatic positional control. Apart from solving an immediate problem, this should enable radical changes to be made in test procedure. The development of mechanised loading and the reduction of linkages have probably both been retarded by the risks of uncontrolled displacement. With a method available for the entire elimination of this trouble there is increased scope for progress in both these directions, with consequential saving of time and effort and increase in the accuracy and usefulness of strength testing.

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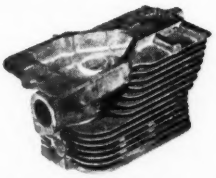

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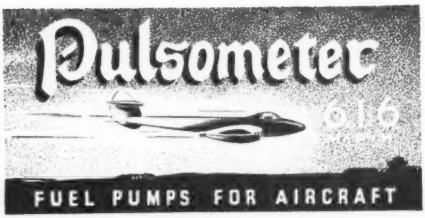

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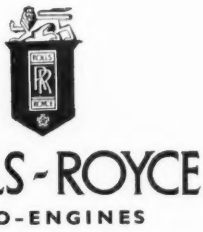

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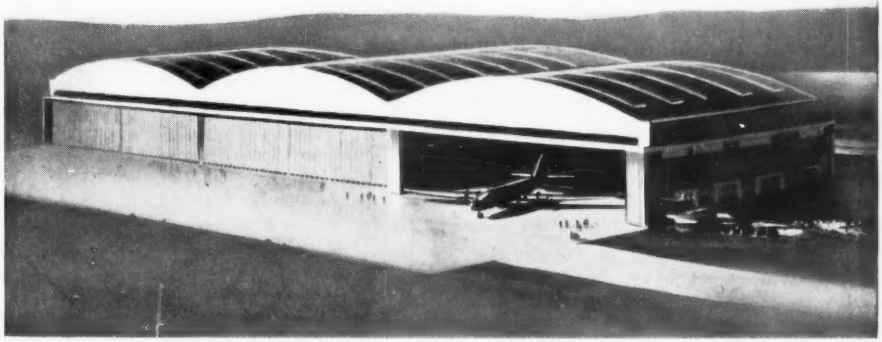

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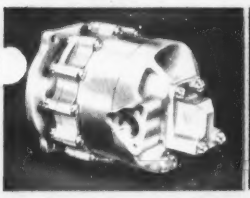

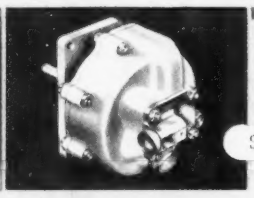

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